Biomechanics of Explosive Sports Skills

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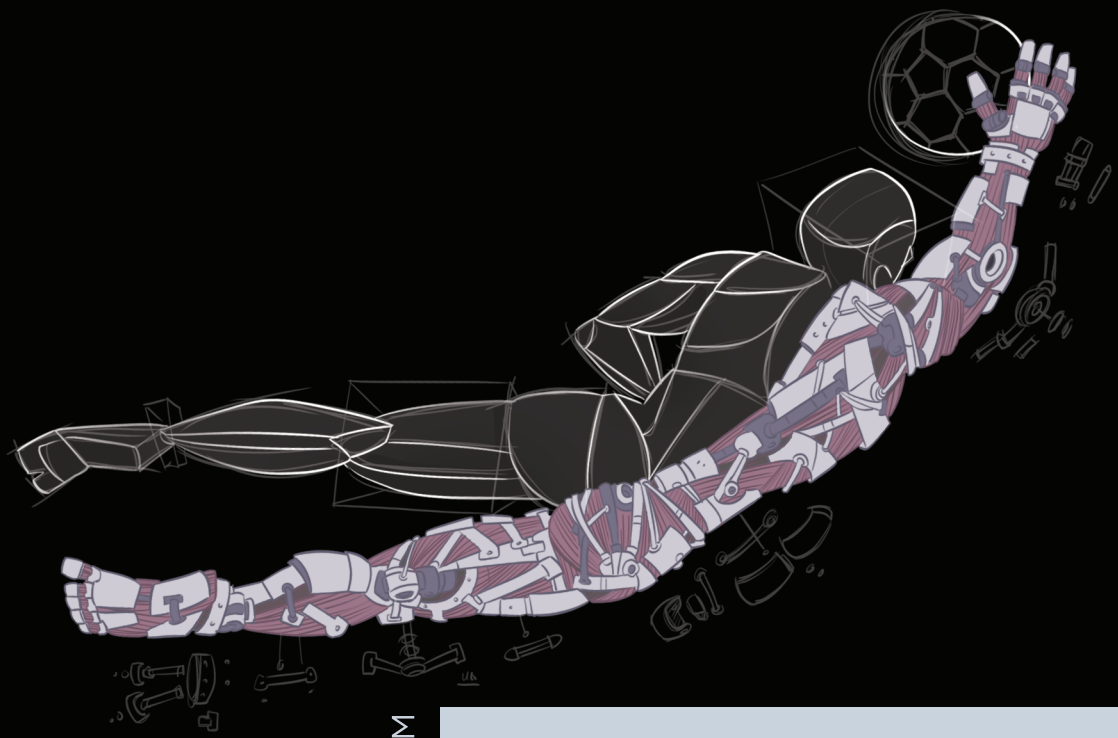

Rony IBRAHIM

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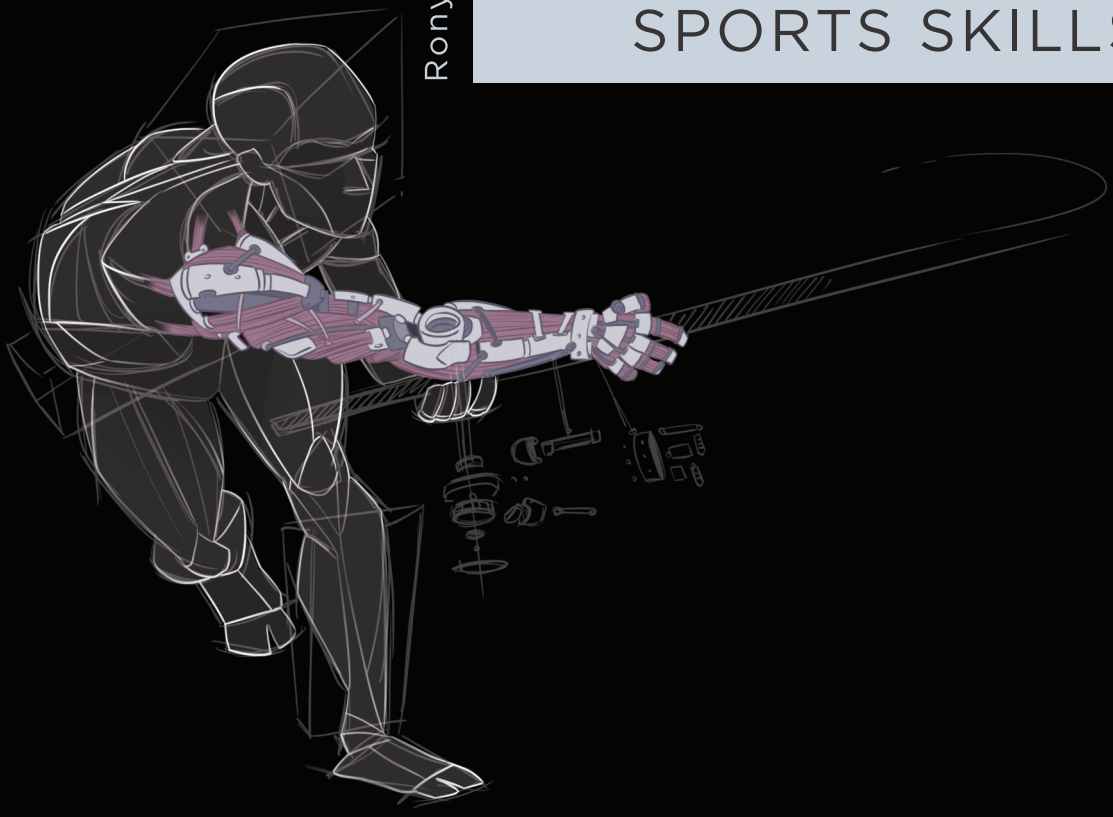

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CHAPTER I

General Introduction

Rony Ibrahim

Athletic performance in sports skills usually involves movements in multiple joints, coordinated in a unique way, and dependent on the technical and physical capacity of the athlete. The kinematic and kinetic aspects of joint actions used in these skills have been the subject of studies by biomechanists. Kinematics involves the analysis of movement variables in body segments associated with joints, such as velocity and acceleration, whereas kinetics involves the identification of forces or moments that cause these movements. Both analyses together allow us to reveal the unique joint coordination that forms the technique of a certain sports skill. Many sports include rapid actions of an offensive (e.g. kicking, throwing, hitting) and defensive (e.g. jump block, goalkeeper's diving save, baseball bat) nature. The movement patterns used are often very explosive, lasting for less than one second, and requiring abrupt accelerations in a very short period of time[5].

The general aim of this thesis is to explore to what extent dominant theories on performance of explosive actions can be used to understand and improve two sample explosive sports skills. We will start by exploring offensive shooting skills and defensive jumping skills biomechanically. Subsequently, we will pick one skill of each, and dig deeper into their analysis in order to understand how they are best executed and how their performance can be improved.

Offensive shooting skills

In football, players kick the ball to score goals; in track and field, athletes throw a javelin, shot put, or discus as far as possible to win; in field hockey, players drag and flick or hit the ball to score goals; in baseball, pitchers throw the ball to the

catchers with the aim of preventing the batter to hit the ball. An important aspect of these skills is to accelerate the distal end as much as possible while maintaining, in most of these skills, high accuracy. The distal end is considered to be any point on the most distal segment or object for which the direction and speed of motion are useful in describing the outcome of the skill, e.g. the hand in a throwing skill or the racket in a tennis serve.

Linking biomechanical principles, such as the principle of optimal coordination of partial momenta and the summation of speed principles, to coaching practices of explosive shooting skills, has been attempted in the literature[14,43]. The principle of optimal coordination of partial momenta proposes, based on mechanical considerations, that distal end velocity is maximized if all the relevant joints reach their peak angular velocity simultaneously and joint angles provide the longest moment arm relative to the distal end (i.e. full extension of relevant joints) at the moment of release[43]. In contrast, the summation of speed principle considers the human body as a linked segment model and states that in order to maximize the speed at the most distal part of the model, the onset of the movement should be launched by the heaviest proximal part. As the kinetic energy increases, it is transferred to the lighter distal segments such that each distal segment in the model starts its motion when the preceding (proximal) segment reaches peak velocity; subsequently it reaches a higher velocity than the preceding segment[14]. There was no clear theory-to-practice interpretation of both principles in the related sports disciplines, which lead to great efforts and studies to reveal and analyse coordination patterns adopted in offensive shooting skills.

On the one hand, there is more empirical support for the summation of speed principle, as athletes from different sports disciplines performed most of their offensive shooting skills in a proximal-to-distal sequence[1,26,78,98,99]. For instance, Alexander and Haddow (1982) measured and analysed upper limb segments motion during the execution of the softball windmill pitch. They found a definite proximal-to-distal sequence in upper limb segments velocities, with decelerations occurring in the proximal segments prior to release of the ball. Similarly, handball players throw the ball in consecutive actions of body segments from larger proximal segments to the relatively smaller distal segments, allowing an optimal flow of kinetic energy to the ball[33,52,73]. Effective summation of body segment speed was also evident in the tennis serve, which is characterized by increased maximum linear velocity of segments in a proximal-to-distal sequence from the knee to the racquet[26,98]. Likewise, one of the main indicators of a successful javelin throw is an orderly progression of peak speeds at the hip, shoulder and elbow from the onset of double leg support until release[99]. Moreover, handball throws and volleyball spikes equally follow a proximal-to-distal sequence in the acceleration phase of the movements[98].

Further support for the principle of summation of segment speeds and the proximal-to-distal sequence, was found when examining the motion-dependent interaction between adjacent lower extremity segments during kicking actions[77]. Additionally, computer simulation of several throwing techniques, also deduced that the greatest distal-end velocity was obtained with a proximal-to-distal sequence[41]. Likewise, computer modelling studies of overarm throwing have demonstrated that maximal throwing speed occurs at a specific delay between proximal

and distal muscle activation: approximately 100 ms between shoulder flexor and rotator muscles[2], and approximately 50 ms between elbow extensors and wrist flexors[20].

On the other hand, the inconsistency in the measured variables and interpretation of the summation of speed principle, and the level of athletes included in the studies, have led also to findings that are not always in line with the above. For example, Fradet et al. (2007) studied the kinematics of handball throws, and found a coordination in joints rotations that is not in line with a proximal-to-distal sequence. Peak shoulder linear velocity occurred after peak elbow linear velocity, and peak trunk angular velocity occurred after peak elbow angular velocity. Similarly in handball, a later study revealed that there is a proximal-to-distal sequence for the initiation of joint movements, but not for peak linear joint velocities[95].

In tennis, Deporte et al. (1990) found that tennis players execute the forehand shot according to the principle of optimal coordination of partial momenta. Additionally, Liu et al. (2010) found that elite javelin throwers developed maximum joint centre linear velocities in a proximal-to-distal sequence (hip, shoulder, elbow and wrist). However, they found a deviation from the proximal-to-distal sequence in the initiation of segment and joint angular motions, as shoulder internal rotation started non-significantly after elbow extension. Similar findings to the latter initiated a debate suggesting that the summation of speed principle is incomplete, as segment rotations around the longitudinal axis (i.e. upper arm internal rotation and forearm pronation) were revealed to be main contributors to the distal-end velocity while not fitting in the proximal-to-distal sequence[34,44,64,88,94]. Explanations of these findings have

been related to bi-articular muscle characteristics of the upper limb[30], the relative large contributions of these rotations to the speed and accuracy of the movement[16,88,94], and interaction forces between segments[35,78].

The drag flick in field hockey

Field hockey, or simply hockey, is a high physically demanding and explosive team sport. Given the fact that around 33% of the goals in hockey are scored from penalty corners, the ability to score in this game situation is considered to be the most important and determining factor in winning a match[60]. When hockey balls started to threaten players' safety, the international hockey federation restricted the height of ball shots, performed by hitting the ball with the stick, strictly below the backboard level. If a high shot is the aim of the player, then the rules dictate that he/she has to carry and push the ball with the stick, instead of hitting it. This of course decreased the linear velocity of high balls which made the game safer. However, it did not take so long until a new shooting technique 'the drag flick' was spotted in the Netherlands during the early 90's, allowing for high velocity high shots while abiding to the rules of the game. So far, it is the most effective shooting technique in terms of speed and accuracy, within the rules of field hockey[66,74,106]. Therefore, when it comes to penalty corners, this technique is most often used. The hockey player or the drag flicker (a hockey player specialized in performing drag flick shots) approaches the ball in a semi-crouching position, then picks it up on the shaft of the stick while keeping the latter in an upright position. The ball is then dragged forward from behind while the player flexes the torso further by bending at the waist and finally the ball is released towards the goal in an

explosive flicking motion.

The drag flick is considered an offensive shooting skill, however, it is one of the least studied shooting skills. Due to its unique nature, the biomechanics of the drag flick cannot directly be inferred from studying other offensive shooting skills, such as throws (e.g. baseball pitching), strikes (e.g. smash in volleyball) or hits (e.g. tennis serve). Even though these skills share the same intention with the drag flick, which is reaching a maximal release speed with maximum accuracy; several dissimilar aspects exist between them. Unlike most hitting and throwing skills, the drag flick does not start with a back swing, or what is usually described in other skills as a movement in the opposite direction of the target. In addition, the semi-crouching shooting position of the hockey player is not a common posture in powerful hitting and striking actions, such as baseball batting, tennis forehand, golf shot. Finally, in most of the closed kinetic chain hitting skills both hands are placed as close as possible to each other, allowing similar movement in both limbs as one arm usually leads the other, without any interaction between limbs due to the short moment arm for each hand relative to the other. However, hockey players perform the drag flick while grabbing the stick with the left hand at the top and right hand relatively low on the stick. The usual distance between hands is longer than in other skills (e.g. baseball batting, golf shot, tennis backhand) allowing one wrist to rotate the stick around the other, which seems like a unique wrist joint function in comparison to various other offensive shooting skills. Few researchers have tried to study and analyse this complex multi-joint skill, however until now none of them has succeeded in revealing the underlying mechanisms[63,65]. Therefore, chapter two of this thesis aims to

unravel the coordination pattern of elite hockey players and Olympic level drag flickers performing the drag flick shot, by turning back to the two previously mentioned principles. The contribution of joint rotations to stick-head speed will also be analysed in order to have a complete kinematic description of this skill.

Defensive jumping skills

In volleyball, players jump to block opponents' attacks; in basketball, players jump to block a shot to their home baskets; in football, goalkeepers dive to save balls shot towards their home goals.

The main aim of this kind of skills is to perform an explosive push-off, propelling the body in the air to be able to deflect the ball trajectory. The push-off that is present in these skills, is a common pattern found in explosive sports motions that include jumping, sprinting, etc. The athletes performing these tasks are time-constrained to build-up kinetic energy, where the magnitude of kinetic energy at takeoff relies largely on the rate of force development (RFD). Therefore, they would benefit from any pre-takeoff movement that does not require much time to execute, yet would enhance the generated kinetic energy during push-off. A so-called countermovement, a movement in a direction opposite to the goal direction, is the most commonly adopted pre-takeoff movement. This movement has received substantial consideration in the scientific literature, especially in the context of vertical jumping tasks[3,13,27,40]. In vertical jumping, the countermovement can be described as a rapid knee flexion, during which the body centre of mass (COM) drops before being propelled in the aimed

direction. The countermovement allows the knee and hip extensor muscles to build up an active state and store elastic energy prior to the push-off, by lengthening them under tension (the stretch cycle). Thereafter, during the push-off phase, the knee and hip extensors start to shorten from an active state with stored elastic energy, which allows for an unchanged RFD (RFD stays the same regardless of whether the muscles are shortening with or without the stretch cycle), to reach a greater peak force during push-off[13,40]. Together, the countermovement and the jump form a stretch-shortening cycle that allows the knees and hips extensor muscles to generate, store and use substantial elastic energy[57]. Some studies have found that the stored elastic energy increases peak power during push-off[4,58], while others found that it improves the efficiency of doing positive work but does not change the total work that can be done during push-off[3,6,13].

As previously mentioned, knee flexion is the mechanism underlying the countermovement. A larger knee flexion, up to a certain optimum, will be translated in a greater countermovement, which will result in a higher and more explosive jump. But pre-takeoff time is increased by 71 to 76% by the countermovement (in countermovement jump), when compared to direct push-off from the same knee flexion angle as obtained during countermovement at the start of push-off[40]. Thus, even though a countermovement increases power output, it also increases execution time. Most likely, the utility and optimal magnitude of a countermovement depend on the relative importance of maximizing jump height and minimizing execution time, as well as the sports discipline (e.g. football, basketball) and many other variables (ball velocity, ball position relative to the target, ball position relative to the defending

athlete, etc.).

The proximal-to-distal sequence was not only found to be prominent in offensive shooting skills, but also in defensive jumping skills[11,12,18,72,96]. Proximal-to-distal sequence in hip, knee and ankle, was found by analysing peak vertical velocity differences between the ends of segments and peak muscle activation[11]. The authors explained this sequence by referring to the function of the mono-articular hip and knee extensor, and ankle plantar flexor muscles. A proximal-to-distal sequence allows these muscles to shorten over their full range and ensuring a balanced contribution of segmental angular velocities to COM vertical velocity[12]. This coordination in muscle activation was also found to be the optimal strategy for maximum jump height in a study that modelled vertical squat jumping[72]. Finally, this sequence was found to be promoted when arm swing was included in the jump, and to result in greater net joint moments and segment accelerations of the lower limb[18].

The diving save in football

The goalkeepers in football have a unique position on the field, aiming to defend the goal by not letting the ball cross the goal line. The diving save is the main technique used by goalkeepers to deflect the trajectory of the ball away from the goal. It is a complex motor task characterized by large forces exerted at push-off, in different directions and by the necessity to generate these forces in a very short period of time. Hence, it is considered a defensive jumping skill similar to the ones described above, but with timing probably playing a role as significant as jump performance. Yet the diving save is still not well studied from a biomechanical point of view. Full

kinematic and kinetic analysis of the diving save have not yet been performed, and the underlying mechanism of this skill is yet to be unravelled in order to align the technical and physical training with the needs of goalkeepers.

Only two studies have analysed the mechanics of the diving save and they were incomplete, both kinematically and kinetically[87,90]. Therefore, chapter three will present a study with the aim to investigate the effect of the preparatory stance of the goalkeeper, linear and angular momentum coordination, and leg contributions to the diving save performance. Thereafter, chapter four will focus on lower extremity joint powers, moments and angular velocities, during the diving save in a close-to-reality experimental set-up. Additionally, the timing of these variables is investigated in order to reveal the extent to which they show a proximal-to-distal sequence.

Finally, chapter five will aim to determine the optimal preparatory stance of the diving save. In explosive defensive tasks that are time restricted, like the diving save, the characteristics of the preparatory stance can have a major influence on performance[7,103]. In addition, building upon the findings presented in the third chapter, the coordination between linear and angular momentum, which are the results of the generated forces and moments, need to be carefully controlled for each dive height. For instance, when considering the ultimate position to be reached with the hands during the diving save, it can be assumed that high dives require the production of a small angular momentum during the pre-push-off phase, and then a larger and explosive linear momentum at push-off. Whereas, low dives require a large and explosive generation of angular momentum during the pre-push-off

phase, followed by a relatively smaller linear momentum at the actual push-off. The stance width in the starting position may be a key factor for generating the required angular momentum, as foot position determines the moment arm of the ground reaction force relative to COM. Knee angle in the starting position may be a key factor in generating linear momentum, as countermovement range is affected by the starting knee angle. Therefore, the main focus in chapter five will be the knee angle and stance width selected for the preparatory stance. Self-selected preparatory stance will be analysed and compared to other imposed positions. Finally, chapter six will discuss the applicability of both principles presented here to twhe two skills studied, and to their technical and physical training.

CHAPTER II

Kinematic Analysis of the Drag Flick in Field Hockey

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Abstract

Attaining high speed of the stick head and consequently of the ball is essential for successful performance of the drag flick in field hockey, but the coordination pattern used to maximise stick head speed is unknown. The kinematics of the drag flick was studied in ten elite hockey players who performed twenty shots each towards a target located 1.5 m high. A 150 Hz active marker motion analysis system was used, alongside two force plates to detect foot touchdown. Angular velocity and contribution to stick endpoint speed of upper body joints were analysed. Repeated measures ANOVA was used to compare timing of onset and peak angular velocities between joints. Participants used a kinematic pattern that was close to a proximal-to-distal sequence. Trunk axial rotation and lateral rotation towards the target, right wrist flexion and left wrist extension were the main contributors to stick endpoint speed. Coaches should emphasise trunk rotations and wrist flexion and extension movements for maximising stick head speed. Given the high level of the participants in this study, the coordination of joints motions, as reported here, can serve as a guideline for drag flick training.

Keywords:

Proximal-to-distal; stick; 3D kinematics; strength and conditioning; kinetic chain

Introduction

When aiming to improve athletic performance, a thorough analysis of skilled performance assessing the functionality of its characteristics is fundamental. Several researchers have studied explosive throwing, hitting and kicking skills in this way and found that highly skilled athletes usually accelerate the end effector (i.e. hand, foot, stick, club, etc.) by initiating the movement with the heaviest, proximal segment (i.e. trunk) followed by a proximal-to-distal sequence[25,53,61,64,79,97]. This has been described as the 'kinetic link principle', which states that kinetic energy of a segment is transferred to the adjacent, distal segment, as soon as it reaches its maximum, such that each segment starts or accelerates its motion relative to the proximal segment, when the adjacent proximal segment reaches its peak velocity[64,78]. In contrast with the observed strategy, the 'principle of optimal coordination of partial momenta' [43,78] predicts based on mechanical considerations that the speed of the end effector would only be maximised, if all the relevant joints would simultaneously reach their peak angular velocities and be fully extended to have the longest moment arm relative to the end effector. However, anatomical and physiological constraints make the kinetic link principle the more commonly adopted and most likely optimal strategy[13,25,61,78,79,97].

The drag flick is an effective shooting technique in field hockey, especially when it comes to the penalty corner[65,74,106]. As opposed to hitting the ball, the drag flicker is allowed to elevate the ball at goals, thus making it a much more threatening alternative to hitting from the penalty corner as direct hitting shots on goals are not allowed to be above backboard height (46 cm). The drag flick is a multi-joint coordination task that

involves both upper limbs in a closed chain. The rules of field hockey constrain the athlete to drag the ball along with the stick head and then flick it, instead of just hitting it as in other closed-chain shooting tasks (e.g. baseball batting, golf swinging). However, as in other single and double limb throwing and hitting tasks, the aim of the drag flick shot is to shoot the ball as accurate and as fast as possible.

Previous studies identified a wide stance and a whipping action of the stick followed by explosive sequential rotations of the pelvis, upper trunk and stick as determinants of a successful drag flick[63,65]. However, the information provided by these studies was limited by either limitation in instrumentation, in particular a limited sample rate, or the skill level of the participants. Furthermore, both studies only analysed the kinematics of the pelvis, thorax and stick, and neglected the kinematics of the upper limbs. Therefore, the goal of this study was to conduct a comprehensive 3D kinematic analysis of the drag flick in elite athletes.

Based on the preference for a proximal-to-distal sequence in throwing and hitting motions reported previously, it could be hypothesised that hockey players follow the kinetic link principle and adopt a proximal-to-distal sequence in the drag flick. However, unlike previously studied sports movements, the drag flick is performed with two arms in a closed loop and with extended contact between the implement and ball; hence, conventional proximal-to-distal sequencing might not be fully satisfied. Furthermore, we hypothesised that the trunk segment and all upper limbs joints contribute substantially to the endpoint speed.

Methods

Ten male field hockey players, mean ± standard deviation age 25 ± 3 years, mass 83 ± 5 kg and height 183 ± 3 cm, participated in this study. The participants were the following: three Olympic-level drag flickers, four national-level drag flickers and three Olympic-level hockey players (not specialised in drag flick). Before performing the experiment, participants signed informed consent. For each participant, anthropometric data, age and injury history were gathered. The participants did not suffer from an injury that prevented them from performing the drag flick at their maximal power or caused them to adapt a different movement pattern. The Ethics Committee of the Faculty of Human Movement Sciences of the Vrije Universiteit Amsterdam had approved the research protocol.

Data collection and pre-processing

Before starting the measurements, the athletes performed a warm-up routine, which included a number of progressively faster drag flicks. Each participant was then instructed to perform, using his own stick, twenty drag flicks with the ball positioned 13 m centrally in front of a target, which was at a height of 1.5 m. This target height is considered to be the most common for drag flicks in game situation, given the fact that players are allowed to perform low shots, below backboard height (46 cm), by hitting the ball instead of pushing it.

An active marker motion analysis system (Optotrak 3020, Northern Digital Inc., Ontario, Canada) was used after calibration with a cube with 16 markers. The system consisted of four arrays, containing three cameras each. It was used to capture, at 150 Hz, 3D coordinates data of twenty-seven markers. Eight

cluster markers were strapped on different body segments (shanks, pelvis, thorax, upper arms and forearms), and the thighs were modelled between the shanks and pelvis, in order to obtain a full body model. In addition, three single markers were attached to the stick (1 marker on the shaft and 2 on the stick head). Anatomical coordinate systems of the segments were related to the corresponding marker clusters by digitising specified anatomical landmarks (Appendix 2.1) using a probe with six markers[15]. In the same way, the edges and endpoint of the stick were related to the markers on the stick. A dynamic 3-D linked segment model was used, wherein shoulder joint centre position was estimated based on the work of De Leva (1996) and shoulder rotation was the motion of the upper arm with respect to the trunk. Details of the original model and the modifications for more accurate anatomical modelling of the body segments can be found elsewhere[31,32,55].

Two custom-made strain gauge-based, 1 x 1 m, force plates (Vrije Universiteit, Amsterdam, The Netherlands) were used in order to measure the timing of right and left foot touchdown. Force plates and drag area were covered by artificial hockey grass (Figure 2.1).

Two high-speed cameras were used to visualise the motion. The first camera was placed on the right side to capture, at 240 Hz, the motion in the sagittal plane and was not used for data analysis (Casio EX-ZR1000, Casio Computer CO., LTD., Tokyo, Japan). The second camera was placed above the drag area to capture, at 140 Hz, the motion in the transverse plane and it was also used to detect ball release and calculate ball speed (Basler avA1000-100gc, Basler AG, Ahrensburg, Germany). A LED light turned on when the Optotrak system started

recording, and was used to synchronise Optotrak with the top camera. The top camera provided projected ball speed instead of actual speed. However, the projection error is rather small and constant between trials, and this does not affect the result of this study because ball speed was only used as a selection criterion.

Due to the fact that the drag flick is an explosive movement with a large range of motion, gaps in the kinematic data occurred occasionally when markers were out of sight. These gaps were interpolated using a cubic spline function, for a maximum gap length of three samples. Subsequently, a bidirectional second-order low-pass Butterworth filter with a cut-off frequency of 15 Hz was used, to smooth the data.

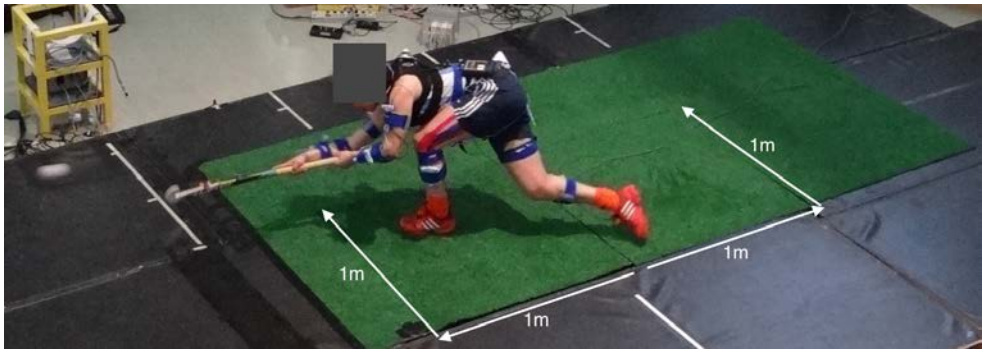

Figure 2.1. Photograph of the drag flick shot that was performed during the experiment. The two force plates (1 x 1 m), which were covered by Astroturf, are highlighted.

Data analysis

Detection of ball release

Agreement between ball release detected from the video analysis (top camera) and from peak stick linear velocity in

the direction of the target[51] was assessed using the Root Mean Square Difference (RMSD). We found an average RMSD over participants of 3.4 ms, which supports the validity of both methods. In this paper, ball release was based on the latter method.

3D Kinematics

All kinematic analysis was carried out using custom software in MATLAB (R2012b, MathWorks inc. US). The angular velocity of the trunk segment (ω_T) was calculated with respect to the global coordinate system[10]. The angular velocities in shoulders, elbows and wrists were calculated by first expressing the velocity of the distal segment relative to the proximal one and then using the equation of Berme and Capozzo (1990). Given the difficulty of measuring the 3D kinematics of the hand, we assumed that the hands and stick rotated together as a rigid unit. The wrist angular velocity was calculated as the angular velocity of the stick with respect to the forearm. The drag flick is initiated by a sidestep jump, followed by right foot touchdown, ball pickup, left foot touchdown, drag phase, flick phase and follow-through. The drag phase starts at left foot touchdown, and it occupies the largest percentage of shot time and serves to accelerate the ball up to a high speed after which the ball is further accelerated in the subsequent flick phase. Based on the opinion of coaches and players, the start of the flick phase is indicated by the onset of right wrist flexion and during this phase the actual shooting motions take place. Only angular velocity components that reached a substantial peak angular velocity during the flick phase, i.e., on average higher than 300 $°\cdot s^{-1}$ were selected for analysis of the adopted kinematic pattern.

Contribution of joints motions to stick endpoint velocity

By modelling the hockey player, separately for each arm, as a chain with the L5S1 joint as the proximal point and the stick head S as the distal endpoint, and assuming that all body segments in the chain are rigid, the linear velocity of stick head (V_S) can be regarded as the sum of the linear velocities contributed by the absolute linear velocity of the L5S1 joint (V_{L5S1}), the angular velocity of the trunk segment relative to the global coordinate system (ω_T), and the angular velocities at the shoulder, elbow and wrist joints of one upper limb:

$$V_S = V_{L5S1} + \omega_T \times r_{L5S1,S} + \sum_{j=1}^{q} \omega_j \times r_{jc,S} \qquad (2.1)$$

where the subscript j indicates the joint (shoulder, elbow and wrist of the right or left arm) ω_j is the 3D joint angular velocity expressed with respect to the global coordinate system. $r_{jc,S}$ is the position vector from joint centre to the stick head (S), and $r_{L5S1,S}$ represents the position vector from $L5S1$ joint to S. For further clarification, the contribution of trunk rotations to stick head linear velocity is quantified by the term '$\omega_T \times r_{L5S1,S}$', and the contribution of each joint j of the right or left upper limb to V_S is quantified by the term '$\omega_j \times r_{jc,S}$'.

After averaging over participants, we compared the left to the right side of equation 2.1 for each upper limb over time. Our results showed high correlations between the time series with correlation coefficients of 0.99 and an average RMSE of 1.1 $m \cdot s^{-1}$ for both upper limbs, thereby supporting the validity of our 3D model and method. The RMSE between both time series can be explained by errors in calculated joint centre

positions, due to measurement errors (e.g. skin movement, muscle contraction under the cluster, interpolation), and the assumption of rigid segments and pure ball-and-socket joints (no joint translation).

Statistical analysis

Velocity time series were time normalised from left foot touchdown until ball release, and represented as percentage of the normalised time (NT), with left foot touchdown 0% and ball release 100%. All data are presented as mean ± standard deviation. The timing of the noted peak joints angular velocities (Table 2.1), of the best trial for each participant, defined as the trial with the highest ball speed, was compared between joints with one-way repeated measures ANOVA. If the results of one-way ANOVAs showed a significant main effect, then paired t-tests with Bonferroni correction were used to identify between which specific joints the timing of peak angular velocities differed significantly from the nearby peak in another joint. The same was done for the onsets of these distinguished joints angular velocities. Two participants needed to be omitted from the analysis for the left arm due to marker visibility issues. All statistical analyses were carried out using IBM SPSS Statistics 20.

Table 2.1. All calculated joint angular velocities and their peak magnitudes during the drag flick.

Joint	Rotation around x axis mean ± SD °•s-1	Rotation around y axis mean ± SD °•s-1	Rotation around z axis mean ± SD °•s-1
Trunk	Lateral flexion left 614 ± 98 No lateral flexion right	Flexion 223 ± 92 Extension 136 ± 90	Axial rotation left 579 ± 120 No axial rotation right
Right shoulder	Abduction 252 ± 218 Adduction 438 ± 137	Flexion 779 ± 192 Extension 201 ± 99	External rotation 132 ± 279 No internal rotation
Right elbow	No rotations	Flexion 267 ± 81 Extension 660 ± 230	Pronation 293 ± 173 Supination 555 ± 192
Right wrist	Radial deviation 169 ± 150 Ulnar deviation 114 ± 122	Flexion 1389 ± 286 Extension 709 ± 117	No rotations
Left shoulder	Abduction 345 ± 193 Adduction 726 ± 335	Flexion 585 ± 204 Extension 218 ± 208	External rotation 542 ± 92 Internal rotation 435 ± 218
Left elbow	No rotations	Flexion 247 ± 89 Extension 103 ± 165	Pronation 22 ± 273 Supination 238 ± 263
Left wrist	Radial deviation 553 ± 196 Ulnar deviation 230 ± 265	Flexion 1050 ± 205 Extension 976 ± 296	No rotations

Results

Kinematic pattern

Our results showed that the drag phase lasted up to 81.5%, which is the moment when the flick phase started. The ball

travelled a total distance of around 2.5 m from ball pickup to ball release and was released with a velocity of 31.7 ± 2.5 $m \cdot s^{-1}$ towards the target. Selected joint angular velocity time traces are presented for the trunk and right arm in figure 2.3 and for the trunk and left arm in figure 2.4. During the drag phase, right elbow pronation and left shoulder external rotation velocity reached their peak values first. Subsequently, right wrist extension, left wrist flexion, right elbow supination and right shoulder adduction velocity reached their peak values between 60%, and 70% of NT. The drag was then concluded with peaks in trunk axial rotation, left shoulder flexion and left shoulder adduction velocity. For the relevant joint motions (shown in Figure 2.3 and 2.4), figures 2.2 illustrates the peaks during the flick phase and figure 2.5 shows the timing of their onsets (i.e. a change of the sign). A significant effect of joint on normalised peak times ($p<0.001$) was found. In line with the hypothesised proximo-distal sequence, pairwise comparisons (Figure 2.2) showed that the sequence of the torso and left upper limb peak joints angular velocities was (1) torso lateral rotation, left shoulder internal rotation, left wrist radial deviation, and (2) left wrist extension ($p<0.05$). The sequence for the right upper limb joint rotations peaks was (1) torso lateral rotation, (2) right shoulder flexion, and (3) right wrist flexion and right elbow extension ($p<0.05$). In addition, a significant effect of joint on normalised onset times ($p<0.001$) was found. Pairwise comparisons (Figure 2.5) showed that the sequence of onset times of the torso and left upper limb joint rotations was (1) torso lateral rotation, (2) left wrist radial deviation and left shoulder internal rotation, and (3) left wrist extension ($p<0.05$). The sequence for right upper limb joint rotations onsets was (1) torso lateral rotation, (2) right shoulder flexion, right elbow

extension and right wrist flexion (p<0.01).

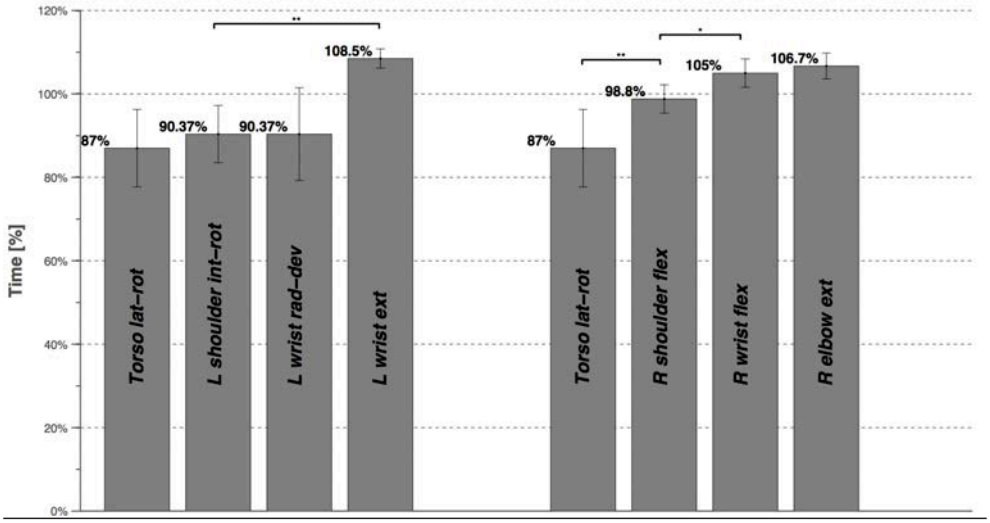

Figure 2.2. Timing of peak joints angular velocity during the flick phase (*p<0.05 and **p<0.01). Left foot touchdown is 0% and ball release is 100%.

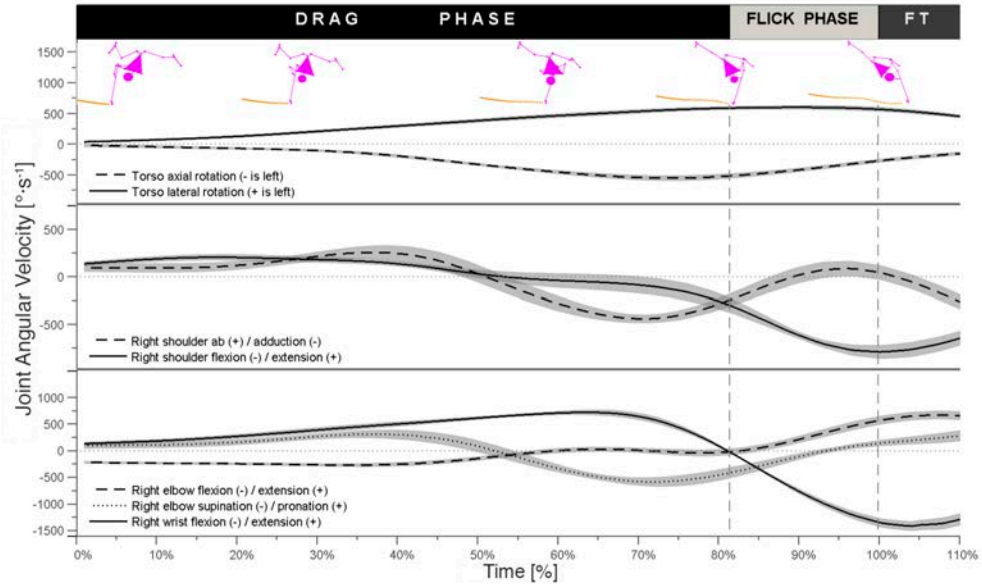

Figure 2.3. Trunk and right upper limb mean joint angular velocity, in black solid and dashed line (refer to the subfigure legend), normalised over time and averaged over participants' best trial, and the standard error in grey shading. At the top, 3 main phases are highlighted: the drag phase, flick phase and follow-through (FT). 5 captures of the 3D model (top-view) are inserted in correspondence to the NT and aim to improve the visualisation of the kinematic pattern.

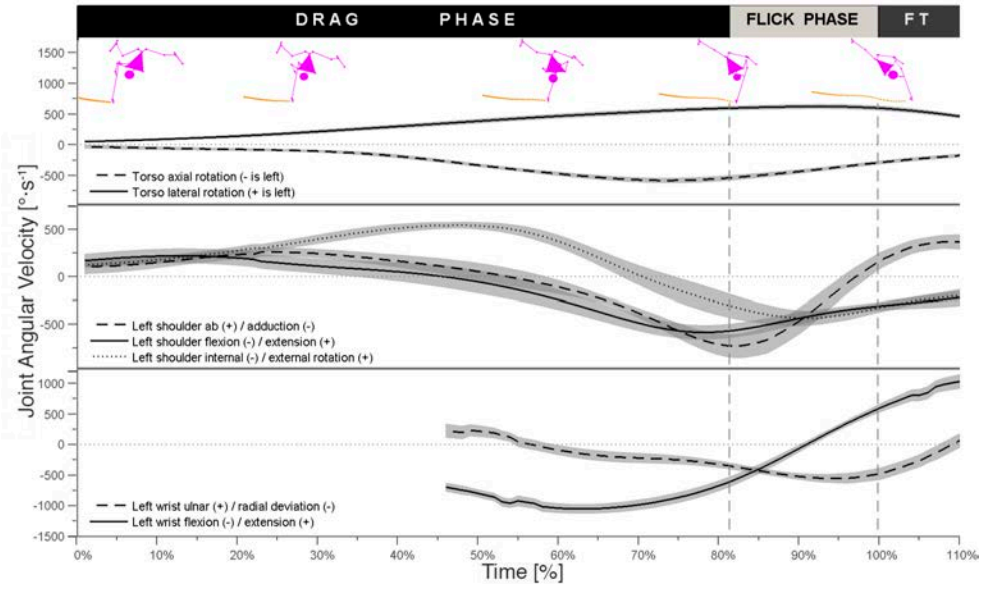

Figure 2.4. Trunk and left upper limb mean joint angular velocity, in black solid and dashed line (refer to the subfigure legend), normalised over time and averaged over participants' best trial, and the standard error in grey shading. Refer to caption of figure 2.3.

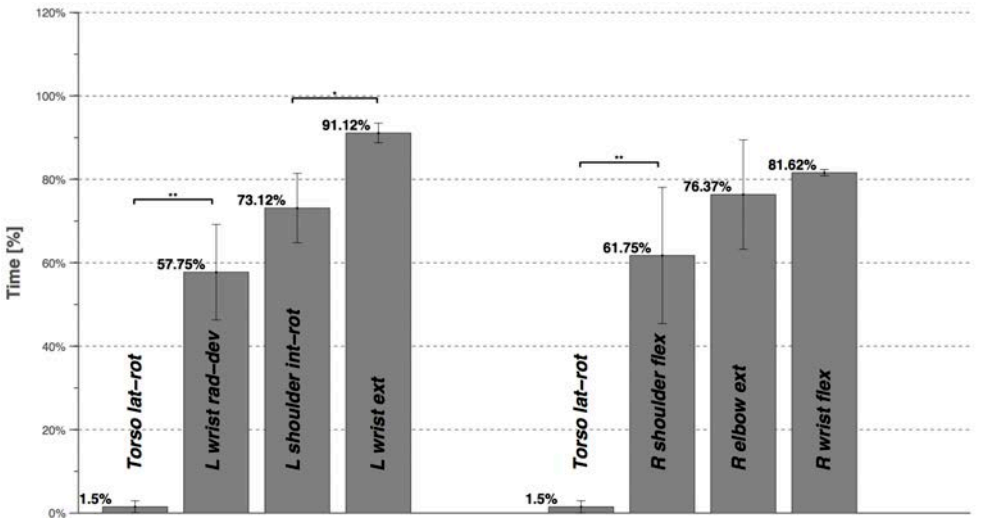

Figure 2.5. Timing of onset joints angular velocity that had their peaks during the flick phase (*p<0.05 and **p<0.01). Left foot touchdown is 0% and ball release is 100%.

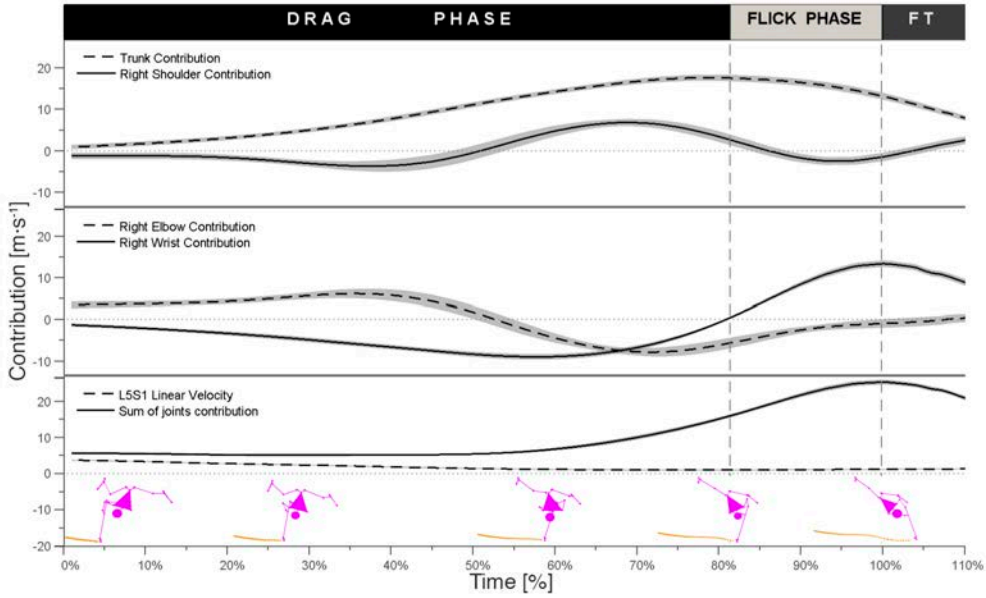

Figure 2.6. Trunk and right upper limb mean joints contribution to stick endpoint speed in black solid and dashed line (refer to the subfigure legend), normalised over time and averaged over participants' best trial, and the standard error in grey shading. Refer to caption of figure 2.3.

Contributions to stick endpoint velocity

During the drag phase, peak negative contributions of the right and left wrist (Figures 2.6 and 2.7) coincided with peak right wrist extension and left wrist flexion (Figures 2.3 and 2.4), corresponding to a phase lag of the stick relative to the right forearm. The right shoulder showed a peak positive contribution during the last part of the drag phase (Figure 2.6), caused by right shoulder peak adduction (Figure 2.3), bringing the upper arm in line with the trunk.

At the end of the drag and start of the flick phase, the left shoulder showed a peak positive contribution, mainly caused by peak left shoulder adduction and internal rotation (Figure 2.4). A right wrist positive contribution started at the onset of the flick phase (81.3 ± 0.8%; Figure 2.6), coinciding with the start

of wrist flexion and with the peak torso positive contribution (Figure 2.3). Subsequently, the right wrist positive contribution reached its peak value at ball release (100.3 ± 2.3%). The left wrist positive contribution started at 87.6 ± 2.7%, significantly later than the onset of the flick and right wrist positive contribution ($p<0.001$). The peak positive contribution of the left wrist occurred at 105.2 ± 2.9%, which was significantly after right wrist peak positive contribution ($p<0.001$) and ball release ($p<0.01$). The main contributors to stick velocity, at ball release were trunk motions (lateral and axial rotation), right wrist flexion and left wrist extension (Figures 2.6 and 2.7), which contradicts our second hypothesis that all joints contribute substantially. The left elbow contribution at ball release was only 3.6 $m \cdot s^{-1}$ with a relatively large standard deviation of ± 4.8 $m \cdot s^{-1}$. Furthermore, shoulder motions and right elbow motions did not contribute positively to stick endpoint speed at ball release.

Discussion and implications

This study describes the kinematic pattern that hockey players use when performing the drag flick. As hypothesised, this pattern corresponded by and large to a proximo-distal sequence, predicted by the kinetic link principle, rather than reaching peaks at the same time in each joint, as predicted by the principle of optimal coordination of partial momenta. However, due to the closed chain formed by the trunk, arms and stick, the drag flick requires some rotations of the distal segments to take place relatively early. For example, during the drag phase, peaks in right elbow supination and pronation velocity corresponded with longitudinal stick rotations made to drag the ball along with the head of the stick. Moreover,

hockey players grab the stick with the hands at different levels, with the right hand placed below the left one, providing a substantial moment arm between both hands.

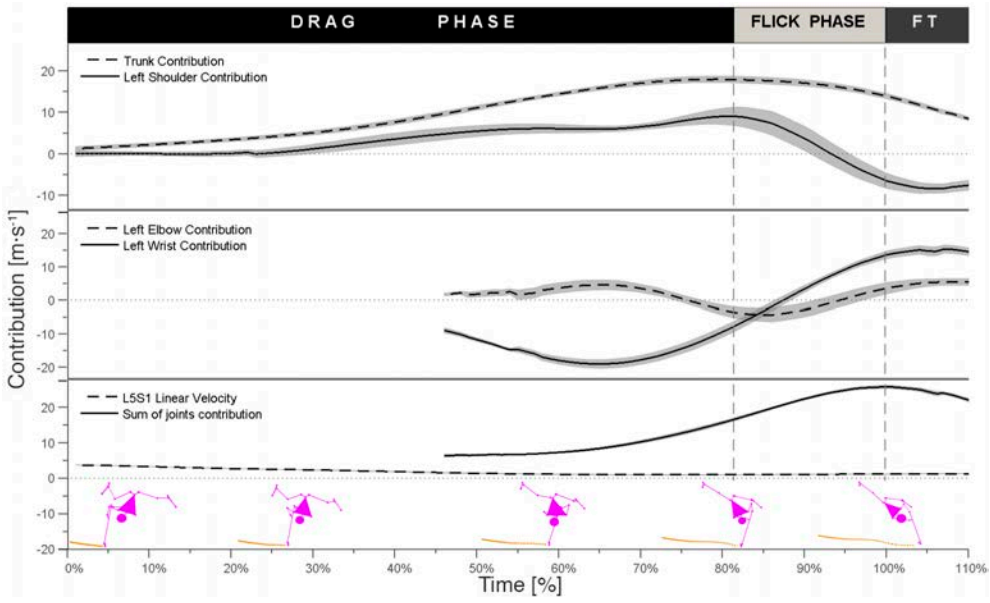

Figure 2.7. Trunk and left upper limb mean joints contribution to stick endpoint speed in black solid and dashed line (refer to the subfigure legend), normalised over time and averaged over participants' best trial, and the standard error in grey shading. Refer to caption of figure 2.3.

During the lag (in the drag phase), left shoulder external rotation occurs to allow right wrist extension while keeping the ball moving in straight line. During the flick, left shoulder internal rotation occurs to allow the flicking motions of the right hand (right wrist flexion), while again keeping a straight ball trajectory. It is also assumed that left wrist radial deviation (90.4 ± 11.1%) was necessary in association with left shoulder internal rotation (90.4 ± 6.8%) given the constraint of the closed chain.

Right wrist flexion reached its peak velocity non-significantly

before right elbow extension, which is in agreement with other ballistic but open chain movements, such as baseball pitching and handball throwing[44,93,95]. This might be due to the presence of biarticular muscles, in this case the wrist flexors. Ettema, Styles, and Kippers (1998) showed that wrist flexor muscles have a substantial moment arm at the elbow. This biarticular function implicates that a flexion moment, caused by right wrist flexor muscles, can cause a flexion moment around the right elbow. Therefore, it can delay peak right elbow extension, which may explain why peak right elbow extension occurred slightly after peak right wrist flexion.

With the exception of the left wrist deviation, figure 2.5 showed a proximo-distal sequence in both upper limbs, but differences between adjacent onset values were not always statistically significant due to the relatively large standard deviation of timing of onsets of shoulder and elbow rotations. One possible limitation of this study is that we analysed rotation about multiple axes for each joint. Reporting one overall resultant angular velocity per joint might seem more useful for analysing the kinetic link principle, because it would avoid interpretation problems caused by having different onset and peak rotation timings about the individual axes within a joint. However, this approach would prevent us from quantifying positive contributions to the speed of the stick head. Figures 2.6 and 2.7 show that shoulders and elbows rotations, in contrast to our second hypothesis, did not contribute substantially to stick endpoint speed around ball release. This becomes logical when considering the directions of the rotations with angular velocities higher than 300 $°\cdot s^{-1}$ in these joints (Figures 2.3 and 2.4). The inconsistency in the onset of shoulders and elbows rotations, may thus illustrate that these rotations are

not essential for increasing ball speed. However, while these joints did not directly contribute positively to ball speed, their role was still pertinent in promoting the effect of motion of the trunk on ball speed. Specifically, they limited the effect of the decrease in trunk angular velocity on the trunk contribution by enlarging its moment arm to stick endpoint.

To explain why athletes adopt the movement pattern described, we highlighted some important time instants by inserting stick figures of the 3D model (top-view) in figures 2.3, 2.4, 2.6 and 2.7. The drag flick demands coordinated movement of multiple joints to push the ball in a roughly straight line from its initial position towards the target. Looking at the stick figures clarifies how the moment arm of stick endpoint relative to the L5S1 joint evolves in time and how the stick endpoint follows roughly a straight line. Shoulders and elbows extend and flex, respectively, early in the drag phase. Subsequently, they start to flex and extend, respectively, at the end of the drag phase. The latter increases the moment arm of the stick endpoint relative to the L5S1 joint, with the longest moment arm around ball release. Moreover, these motions insure a straight ball trajectory when the torso would tend to curve it during flick phase.

One could still argue based on figure 2.6 that if right wrist positive contribution to ball speed would start earlier, it could reach its peak at about the same time as peak trunk contribution (i.e. principle of optimal coordination of partial momenta). Consequently, ball release would occur earlier as well, but with a higher stick velocity, considering that trunk contribution would have been still at, roughly, its peak magnitude. This may be unattainable because at the start of

the flick phase, the right wrist started to contribute positively to stick endpoint speed (Figure 2.6), caused by right wrist flexion angular velocity (Figure 2.3). Simultaneously, the trunk contribution started to decrease due to deceleration of trunk axial and lateral rotations. The transfer of angular momentum from proximal to distal segments, as the distal segments push off relative to the proximal segments when the joints start to rotate, and as the moment arm of the stick increases relative to the L5S1 joint, may be the reasons behind this decrease in trunk angular velocity[24]. In addition, the nervous system may protect the joints by decelerating movements before reaching the anatomical limits[54]. However, it is uncertain which of these mechanisms (or maybe both) plays a role in the drag flick. Future research could analyse the angular momentum and energy flow during the drag flick, along with measurement of muscle activity, to elucidate whether this transfer is due to a mechanical response of the trunk segment to activation of right shoulder muscles that accelerate the arm, or that it is achieved by contraction of antagonistic lower trunk muscles to protect lower trunk joints from reaching their anatomical limits[21,54].

Given the strong non-sagittal plane trunk contribution to endpoint speed, strength and conditioning coaches should probably emphasise training drag flickers' trunk muscles, especially those contributing to dynamic trunk axial and lateral rotation motions, such as the abdominal obliques. Furthermore, right wrist flexion is a main contributor to endpoint speed and might thus be included in dynamic strength training. The shoulder and elbow motions mainly facilitate a long moment arm and a straight ball trajectory, so that coordination may be more important than power generation. These recommendations are

however somewhat premature, given that joint contributions analysed in this study are kinematic contributions and do not directly pinpoint joint moments or muscle groups responsible for generating these movements. Future research needs to incorporate joint moments and measurement of muscle activation, to confirm the implications of our outcomes.

In addition, shoulder rotations calculated by the 3D model, in this study, are a limited representation of arm motion given the fact that we did not differentiate glenohumeral from shoulder girdle motion. The 3D model gives shoulder rotations as the motion of the arm with respect to the trunk, which neglects shoulder joint centre translation and therefore affects the length of moment arm from shoulder to stick head.

Conclusion

In conclusion, we present a detailed report of the kinematics of the drag flick performed by elite hockey players. They used a movement pattern, close to a proximal-to-distal sequence, in which trunk axial and lateral rotations, right wrist flexion and left wrist extension were the main contributors to stick endpoint speed. Shoulder and elbow motions mainly insured a straight ball trajectory and elongated the trunk moment arm to stick endpoint.

Disclosure statement

No potential conflict of interest was reported by the authors.

CHAPTER III

Kinematic and Kinetic Analysis of the Goalkeeper's Diving Save in Football

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Abstract

Kinetics and full body kinematics were measured in ten elite goalkeepers diving to save high and low balls at both sides of the goal, aiming to investigate their starting position, linear and angular momentum, and leg's contribution to end-performance. Our results showed that goalkeepers adopted a starting position with a stance width of 33 ± 1% of leg length, knee flexion angle of 62 ± 18° and hip flexion angle of 63 ± 18°. The contralateral leg contributed more than the ipsilateral leg to COM velocity ($p<0.01$), both for the horizontal (2.7 ± 0.1 $m \cdot s^{-1}$ versus 1.2 ± 0.1 $m \cdot s^{-1}$) and for the vertical component (3.1 ± 0.3 $m \cdot s^{-1}$ versus 0.4 ± 0.2 $m \cdot s^{-1}$). Peak horizontal and peak angular momenta were significantly larger ($p<0.01$) for low dives than for high dives with a mean difference of 55 $kg \cdot m \cdot s^{-1}$ and 9 $kg \cdot m^2 \cdot s^{-1}$, respectively. In addition, peak vertical momentum was significantly larger ($p<0.01$) for high dives with a mean difference between dive heights of 113 $kg \cdot m \cdot s^{-1}$. Coaches need to highlight horizontal lateral skills and exercises (e.g. sideward push-off, sideward jumps), with emphasis on pushing-off with the contralateral leg, when training and assessing goalkeeper's physical performance.

Keywords:

Biomechanics; dive save; push-off; jumping; reaction time; sports performance

Introduction

Optimization of performance in football (soccer), or any other team ball sports, relies on knowledge from disciplines as diverse as biomechanics, physiology and psychology[8,76,101]. In football, the goalkeeper has a unique and critical role in the team, which requires timed and explosive adjustments of body speed, position and orientation in response to a stimulus. Research has mainly focused on the psychological aspects of this task, focusing on perceptual and cognitive skills used in the diving save during penalty kicks[37,59,81,82,100]. Biomechanical studies are scarce, possibly because of the role differentiation between legs and the high impact at landing, which make full-body kinematic and kinetic measurements of the diving save challenging to perform. To our knowledge, only two studies have investigated the biomechanics of goalkeeper's diving saves[87,90]. Suzuki et al. (1987) calculated the path of goalkeeper's centre of mass (COM) in diving to save balls suspended at three different heights (0.30 m, 0.90 m and 1.50 m) at one side of the goal. The measurements were performed on four goalkeepers (two high-level and two novice goalkeepers) in two dimensions and at a relatively low sampling rate of 60 samples/s. The data showed that high-level goalkeepers dived more directly towards the ball, with greater velocity than novice goalkeepers. Spratford et al. (2009) compared dives between goalkeeper's preferred and non-preferred sides. They performed the measurements on 6 goalkeepers (under-20 Australian national team) at a sampling rate of 120 samples/s. They found limited asymmetry in the movement patterns between dive sides: a greater COM net projection angle and greater pelvic and torso rotations at initiation, when diving towards the non-preferred side.

Both studies used balls suspended directly to the side of the goalkeepers (under the high post), constraining them to perform a frontal plane dive. This is different from the diving save performed in game situations, where the goalkeepers prefer to dive diagonally (sideward and forward), so they can reach the ball at a better angle and effectively reduce the goal area that they need to cover. Moreover, balls were always suspended at one height at a time, allowing for height-specific adjustments and anticipation before the initiation of the dive.

The diving save is a complex motor task characterized by large forces exerted at push-off generated in a very short period of time, and in many cases in absence of prior knowledge of ball location. Therefore, the starting position and the push-off technique are most likely key factors in diving save performance. However, starting position, and dive side and height dependent leg contributions without prior knowledge of ball location, were not studied before. Therefore, the aims of this study were to document the characteristics of the starting position and to analyse how each leg contributes to the dive towards high and low balls at both sides of the goal, in the absence of prior knowledge of ball location. In addition, total body linear and angular momentum were compared between dive heights and sides. Based on goalkeeper coaches' input, the ipsilateral leg push-off (the leg on the diving side) was hypothesized to contribute the most to the diving save. We also hypothesized that high dives would require greater linear momentum, while low dives may need greater angular momentum.

Methods

Ten elite football goalkeepers, mean ± standard deviation age

18.4 ± 2.6 years, mass 82.6 ± 9.1 kg, height 186 ± 2.4 cm, and dominant leg 9 right and 1 left, participated in this study. The participants' level, at the time of the experiment, was as follows: two goalkeepers in the Dutch Eredevisie (the highest level of competition nationally), six goalkeepers in the Dutch Eerste Divisie (the second highest level of competition nationally), and two goalkeepers in the Dutch under-17 Eredevisie (the highest level of competition nationally for players under 17 years of age). Before performing the experiment participants or their parents signed an informed consent form. For each participant, anthropometric measurements, age and injury history were gathered. Participants had not suffered any injury that prevented them from performing the diving save at their maximum power or caused them to change their movement pattern at the time of the experiment. The experiments were conducted at the Adidas miCoach Performance Centre of AFC Ajax. The Ethics Committee of the Faculty of Behavioral and Movement Sciences of the Vrije Universiteit Amsterdam had approved the research protocol.

Data collection and pre-processing

Before starting the measurement, the participants performed a goalkeeper specific warm-up routine with their coaches and around 8 diving saves to get familiar with the experimental set-up. Each participant was then instructed to dive as fast as possible in response to a visual stimulus, to the correct ball side and height. For each participant, two dives were measured for two heights at both sides of the goal, for a total of 8 dives per participant with 2 minutes recovery time between dives. The visual stimulus was produced by an LED board placed at the penalty spot, consisting of four LED lamps indicating the side

and height of the ball to save. The balls were suspended 1 m in front of the goal line, at two heights from the force plates' level (30 and 190 cm). They were attached to a thin rope by a magnet allowing the goalkeeper to hit or catch the ball. The balls could easily be taken off the magnet, so the goalkeepers did not experience any significant resistance when saving a ball. A ball was suspended at low height on one side, and the other ball was suspended at high height on the other side, and they were re-attached to the ropes after each dive, to avoid any anticipation of height and side.

A passive marker motion analysis system (Vicon 612, Oxford UK) was used after calibration with an active wand comprising five markers. Trajectory data from 44 markers was captured using 10 infrared cameras at 200 samples/s (Figure 3.1). Single markers were attached to different body segments in the form of clusters (feet, shanks, pelvis, thorax, head and forearms), the thighs were modelled between the shanks and pelvis, and the upper arms were modelled between the thorax and forearms, in order to obtain a full-body model without occlusion of the markers during the trials and limiting the risk of landing on markers. The markers were attached in a well recognizable pattern to facilitate the labelling with Vicon Nexus Software (version 1.8.5). Soft markers were used on areas that are prone to impact at landing, and 3 single markers were attached to each ball. Anatomical coordinate systems of the segments were marked with single markers and related to the corresponding marker clusters during a measurement in a reference position (T-pose). Details of the 3-D inverse dynamics model that was used in this study can be found elsewhere[31,32,48,55]. Two custom-made strain-gauge based, 1x1 m, force plates (Vrije Universiteit Amsterdam, Amsterdam, The Netherlands) were used to

measure ground reaction forces (GRF) produced by each leg separately at a rate of 1000 samples/s. Each force plate was separately covered by artificial football grass, to prevent any force transfer between force plates. A mattress was placed beside each force plate, to avoid unevenness of the floor level, and to keep the goalkeeper and the marker set-up safe at each landing. We believe that the presence of mattresses at landing areas did not affect the performance of the dive, instead it made the goalkeeper more comfortable with the experimental set-up when diving with the markers attached. Two Basler high-speed video cameras (50 Hz) were used to record all trials in the frontal plane for visual checks.

Due to the fact that the diving save is an explosive movement with a large range of motion, gaps in the kinematic data occurred occasionally when markers were out of sight. These gaps were interpolated using a cubic spline function, for a maximum gap length of five samples. Subsequently, a bi-directional second order low-pass Butterworth filter with a cut-off frequency of 12 Hz was used, to smooth the kinematic and kinetic data. The optimal cut-off frequency was estimated on kinematic data using the equation developed by Yu et al. (1999).

Data analysis

All kinematic and kinetic analysis were carried out using custom software in MATLAB (R2015b, MathWorks inc. US). Six time instants were identified for the diving save: Light signal, dive onset, contralateral peak force (CPF), ipsilateral peak force (IPF), take-off and ball contact.

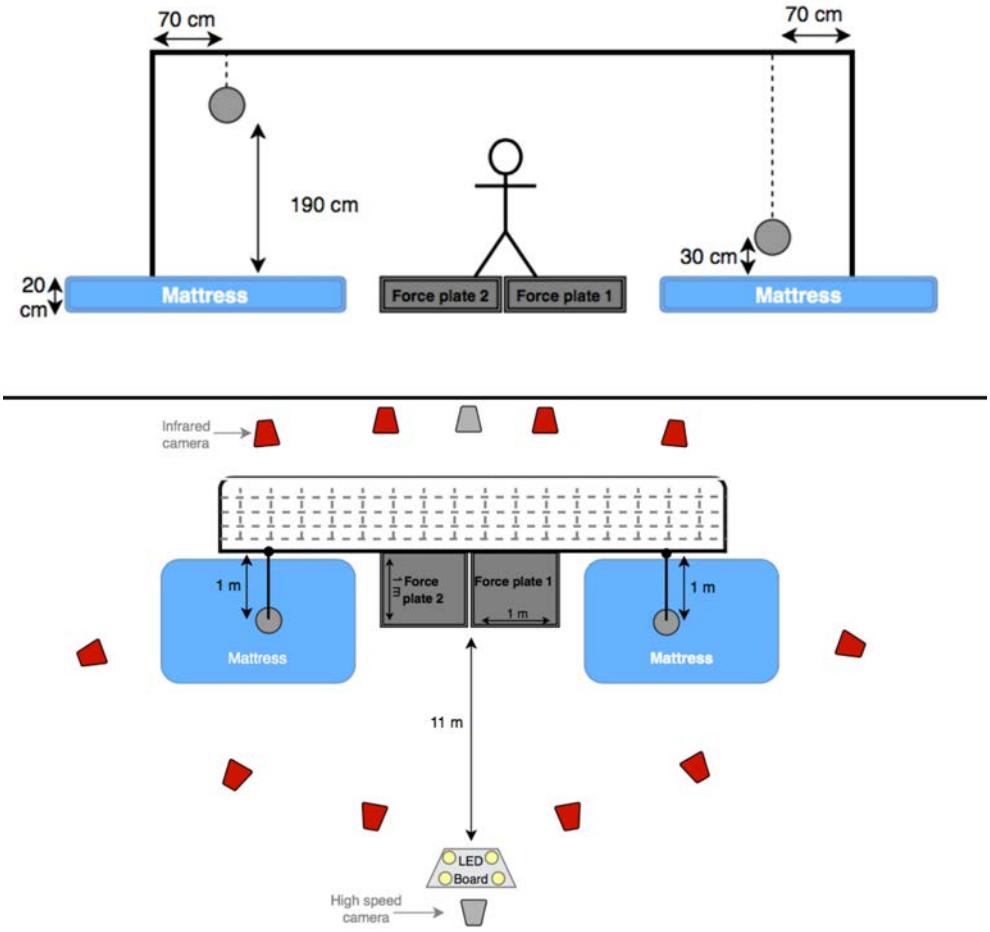

Figure 3.1. Two schematic diagrams of the experimental set-up (front and top view).

Detection of dive onset

For detecting the onset of the dive movement, we used an algorithm based on the Approximated Generalized Likelihood-ratio (AGLR)[89]. Neither this algorithm, nor any other algorithm, has been previously used for onset detection in the diving save. Therefore, a wide scope of data inputs and thresholds

were tested to establish a method to estimate onset time as accurate as possible while preventing any bias. AGLR works by (1) detecting the alarm time (the time instant when the signal reaches the pre-set threshold) using a sliding test window, then (2) tracking back the signal to detect the initial change time using Maximum Likelihood techniques[75]. Eventually, we used a threshold of 20% bodyweight and three different data inputs: (1) Total horizontal GRF, (2) Total vertical GRF and (3) Vertical GRF of the contralateral leg (the leg opposite to the diving side). Different data inputs had to be considered, because the goalkeeper can start the dive by choosing from or mixing these three different strategies: (1) Exerting horizontal forces for horizontal displacement towards the ball, (2) Exerting vertical forces for a pre-push off jump and (3) Exerting vertical forces with the contralateral leg for stepping sideward with the ipsilateral leg towards the ball. While it may seem better to choose the earliest onset from these inputs, sometimes the onset detected from one of the data inputs was slightly too early, due to small movements in the starting position before initiating the dive. Therefore, for each individual dive, the final dive onset was defined as the average of the two out of three onsets, having the smallest mutual difference. Subsequently, total time was split into reaction time (from light to dive onset) and dive time (from dive onset to ball contact).

Kinematics

Timing variables were defined relative to the onset of movement. The instant of contralateral peak force (CPF) was defined as the instant that the contralateral leg exerted its maximum resultant GRF. The instant of ipsilateral peak force (IPF) was defined as the instant that the ipsilateral leg exerted

its maximum resultant GRF. Take-off was defined as the instant that the vertical component of GRF, summed over legs, dropped below 10% bodyweight threshold and ball contact as the instant that a shift in position of the ball's markers was detected in any direction.

The characteristics of the starting position (the body posture at the instant of light signal) included stance width (SW), knee joint flexion angle, hip joint flexion angle and forward centre of pressure (CoP) position. The SW was calculated as the distance between the medial malleoli and was expressed as a percentage of the participant's leg length. The leg length of each goalkeeper was measured from the palpated greater trochanter to the ground while the subject was standing bare feet. The knee and hip joint angles were defined as the Euler angles of the shank anatomical coordinate system (ACS) relative to the thigh ACS, and of the thigh ACS relative to the pelvis ACS, respectively. Their sequence of rotation was: flexion-extension, external-internal rotation and abduction-adduction[102]. The forward CoP was calculated relative to the calcaneus and as a percentage of the participant's foot length (calcaneus to CoP / calcaneus to tip-toe).

Total body linear momentum in the vertical and horizontal direction towards the ball, and frontal plane angular momentum time series were calculated[104] from the light signal to ball contact.

Kinetics

The body COM velocity resulting from the push-off of each of the legs was calculated based on equation 3.1, which is derived from Newton's second law of motion:

$$v_j = \left(\int_{t_0}^{t_{takeoff}} \left(F_j / m - g / 2 \right) \right) / f \qquad (3.1)$$

where v is the velocity [m·s^{-1}] and the subscript j represents the leg side (right or left leg). t_0 and $t_{takeoff}$ indicate light and take-off instant respectively. F indicates GRF [N] of the leg concerned in the calculation, m is the bodyweight [kg], g is the gravitational acceleration [m·s^{-2}] and f is the sample rate [s^{-1}]. The acceleration resulting from each leg's push-off was quantified as:

$$F_j / m - g / 2 \qquad (3.2)$$

Statistical analysis

All time series were time-normalized from the light signal until ball contact. All data are presented as mean ± standard deviation between-subject. Peak magnitudes, and absolute values at CPF and IPF of the time series were compared between heights and sides, and between heights, and contra- and ipsilateral legs, with two-way repeated measures ANOVAs. All statistical analyses were carried out using IBM SPSS Statistics 20.

Results

Our results showed that the starting position of the goalkeepers was characterized by a SW of 33 ± 1% of leg length, 62 ± 18° knee flexion and 63 ± 18° hip flexion. The small standard deviation for SW at the starting position, might be caused by similarities in the coaching systems at the goalkeepers' clubs.

The forward CoP was on average located at 75 ± 12% of foot length from the heel. After the light signal, the goalkeepers stepped sideways with their ipsilateral leg to increase the SW from 33 ± 1% to maximum values of 88 ± 8% and 77 ± 11%, for high and low dives respectively (Figure 3.2). Repeated measures ANOVAs showed that there was a significant effect of ball height ($p<0.01$) on all variables except reaction time (Table 3.1). Whereas there were no effects of side on any of the variables and no interaction effect. Therefore, the figures in the remainder of the paper show the data averaged over sides to allow for a clear comparison between heights.

Peak resultant GRF was larger for the ipsilateral leg than for the contralateral leg in high dives, but the opposite was true in low dives (Figure 3.3). Horizontal linear momentum was significantly greater ($p<0.01$) for low dives than for high dives, at IPF and at the instant that the peak value was attained (Figure 3.4; Table 3.1). The vertical linear momentum was significantly greater ($p<0.01$) for high dives than for low dives, at IPF and at the instant that the peak value was attained. In addition, the angular momentum in the frontal plane was significantly greater ($p<0.01$) for low dives than for high dives, at IPF and at the instant that the peak value was attained (figure 3.5; Table 3.1). The push-off angle formed by the contralateral leg GRF vector and CoP-ball vector at CPF was 34 ± 3° for high dives and 54 ± 4° for low dives, whereas at IPF the push-off angle formed by the ipsilateral leg GRF vector and CoP-ball vector was 41 ± 3° for high dives and 60 ± 4° for low dives.

The maximum contribution to the COM horizontal as well as the vertical velocity towards the ball was larger ($p<0.01$) for the contralateral leg (2.7 ± 0.1 $m \cdot s^{-1}$ and 3.1 ± 0.3 $m \cdot s^{-1}$, respectively)

than for the ipsilateral leg (1.2 ± 0.1 $m \cdot s^{-1}$ and 0.4 ± 0.2 $m \cdot s^{-1}$, respectively), during all diving save conditions (Figures 3.6 and 3.7). Furthermore, maximum contralateral leg contribution to vertical COM velocity was significantly larger for high dives than low dives ($p<0.01$), whereas the maximum contralateral leg contribution to the horizontal COM velocity was significantly larger for low dives than for high dives ($p<0.01$).

Table 3.1. Mean values with standard deviations for total time, reaction time, dive time, and kinematic and kinetic data (** $p<0.01$). Mean differences are also shown.

Variable	High dive Left	High dive Right	Low dive Left	Low dive Right	Mean difference High – Low	Mean difference Left – Right
Total time [s]	1.287 ±0.056	1.284 ±0.097	1.238 ±0.111	1.217 ±0.077	+0.058**	0.012
Dive time [s]	1.076 ±0.069	1.08 ±0.108	1.035 ±0.088	0.987 ±0.101	+0.067**	0.022
Reaction time [s]	0.211 ±0.046	0.203 ±0.039	0.202 ±0.033	0.229 ±0.055	-0.009	-0.01
Peak vertical linear momentum [$kg \cdot m \cdot s^{-1}$]	133 ±52	153 ±15	28 ±10	31 ±16	+113**	-11
Vertical linear momentum at IPF [$kg \cdot m \cdot s^{-1}$]	102 ±24	107 ±15	8 ±11	11 ±19	+94**	-4
Peak horizontal linear momentum [$kg \cdot m \cdot s^{-1}$]	276 ±85	287 ±35	340 ±38	333 ±44	-55**	-2
Horizontal linear momentum at IPF [$kg \cdot m \cdot s^{-1}$]	257 ±29	249 ±33	298 ±35	289 ±36	-40**	8
Peak angular momentum (frontal plane) [$kg \cdot m^2 \cdot s^{-1}$]	29 ±10	31 ±7	40 ±7	40 ±7	-9**	-1
Angular momentum (frontal plane) at IPF [$kg \cdot m^2 \cdot s^{-1}$]	22 ±3	24 ±7	32 ±5	33 ±7	-9**	-1
Peak ipsilateral leg contribution to horizontal COM velocity [$m \cdot s^{-1}$]	0.7 ±0.2	0.6 ±0.1	1.1 ±0.1	1 ±0.1	-0.3**	0.06
Peak contralateral leg contribution to horizontal COM velocity [$m \cdot s^{-1}$]	2 ±0.1	1.9 ±0.2	2 ±0.2	2 ±0.1	-0.1**	0.07
Peak ipsilateral leg contribution to vertical COM velocity [$m \cdot s^{-1}$]	0.5 ±0.3	0.5 ±0.3	0.1 ±0.07	0.1 ±0.1	+0.4**	-0.04
Peak contralateral leg contribution to vertical COM velocity [$m \cdot s^{-1}$]	2.4 ±0.4	2.4 ±0.2	2.1 ±0.2	2.1 ±0.2	+0.2**	0.03

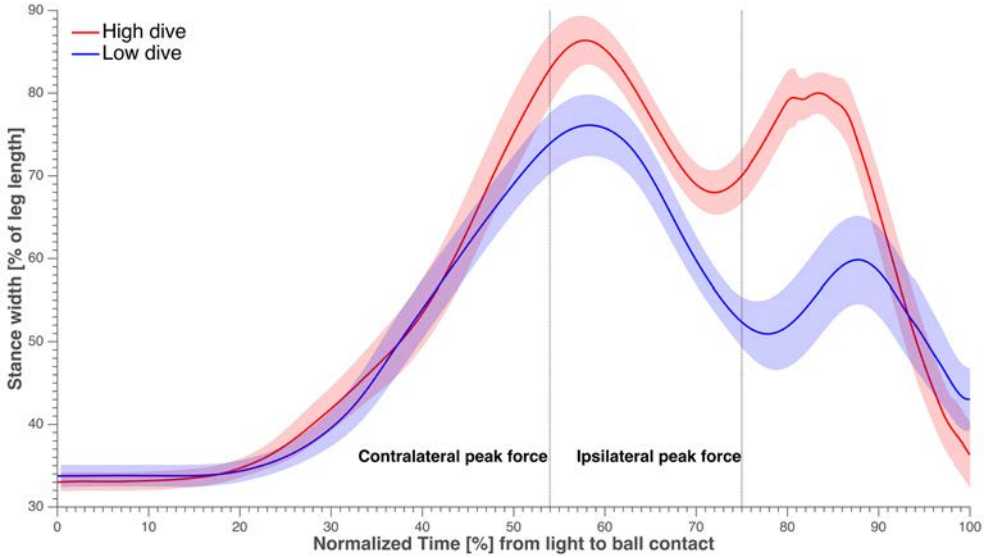

Figure 3.2. The time series of stance width averaged over subjects and sides, normalised over time from light to ball contact, and the standard error in shading. The time instants corresponding to maximum GRF for the contralateral and ipsilateral leg were highlighted.

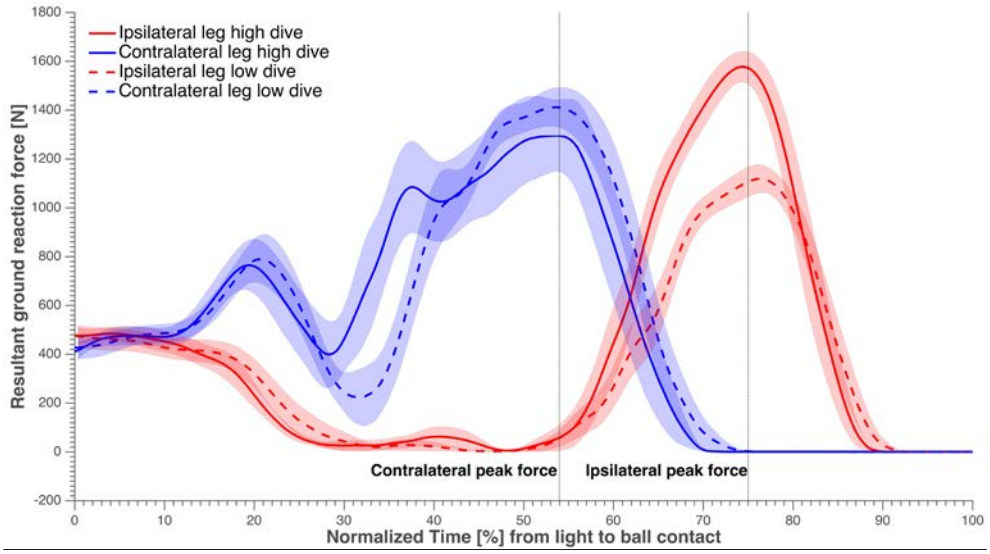

Figure 3.3. The resultant GRF of each leg averaged over subjects and sides, in solid and dashed lines (refer to the figure legend), normalised over time from light to ball contact, and the standard error in shading. The time instants corresponding to maximum GRF for the contralateral and ipsilateral leg were highlighted.

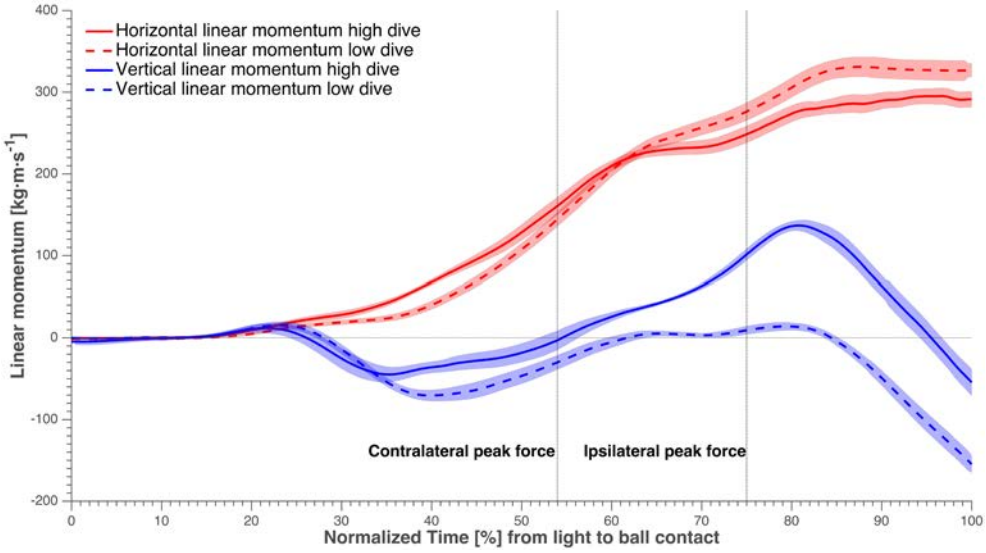

Figure 3.4. Total body linear momentum averaged over subjects and sides, in solid and dashed lines (refer to the figure legend), normalised over time from light to ball contact, and the standard error in shading. The time instants corresponding to maximum GRF for the contralateral and ipsilateral leg were highlighted.

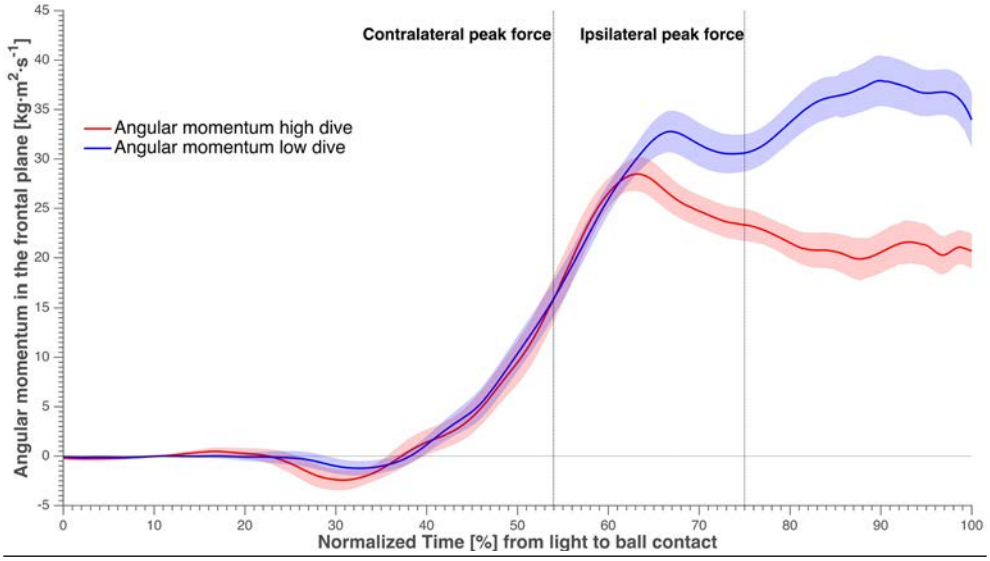

Figure 3.5. Total body angular momentum in the frontal plane averaged over subjects and sides, normalised over time from light to ball contact, and the standard error in shading. The time instants corresponding to maximum GRF for the contralateral and ipsilateral leg were highlighted.

Discussion

This study describes the mechanics of the diving save in elite goalkeepers towards high and low balls, at both sides of their body. Overall, findings were that subjects stepped sideward with the ipsilateral leg at initiation of the diving save. In accordance with our second hypothesis, angular momenta were larger in low dives. Peak linear momenta were larger in vertical direction for high dives and in horizontal direction for low dives. In contrast to our first hypothesis, the contralateral leg contributed more than the ipsilateral leg to COM velocity. There were no significant differences between diving towards the right versus left side on any of the outcome variables (Table 3.1). The latter contradicts the findings of Spratford et al. (2009) on goalkeepers from the Australian youth team. The high level of the goalkeepers participating in the current study may explain the absence of an effect of diving side on any outcome variable. It is clear from the present study that the diving save is a bilateral task involving both lower limbs in explosive push-offs. In addition, placing the ball slightly in front of the goal and using two force plates instead of only one, may have given the goalkeeper more freedom to perform without constraints. The experimental set-up of the current study took into consideration many factors to realistically simulate a game-situation diving save, but one limitation was still that we had the balls hanging in a stationary position.

This study was the first to use automated detection of dive onset. The average calculated reaction time was 211 ± 25 ms, and this is in accordance with previous literature on perception and anticipation during penalty kicks[81,82]. There was no significant effect of height or side on reaction times, in spite of

the differences in force production between these conditions, indicating that the algorithm was not biased by differences in movement strategy.

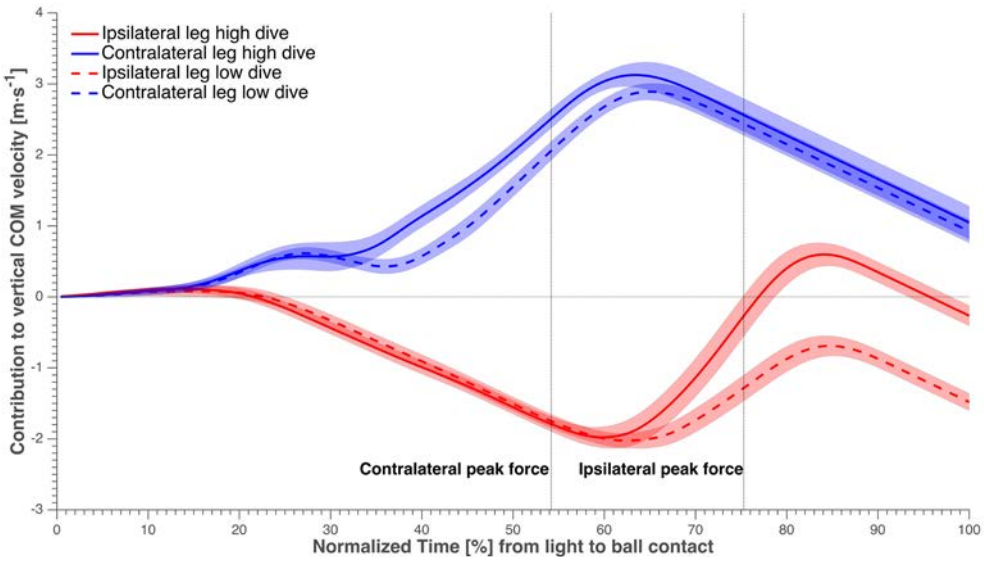

Figure 3.6. The contribution of each leg to vertical COM velocity averaged over subjects and sides, in solid and dashed lines (refer to the figure legend), normalised over time from light to ball contact, and the standard error in shading. The time instants corresponding to maximum GRF for the contralateral and ipsilateral leg were highlighted.

Figures 3.6 and 3.7 showed that contralateral push-off was essential, as the contralateral leg contributed significantly more than the ipsilateral leg to the COM velocity towards the ball. This was in contrast with our first hypothesis, which was based on training recommendations and the emphasis of goalkeeper's technical, and strength and conditioning coaches. The reason behind this might be the fact that the contact time of contralateral push-off (480 ± 71 ms) was significantly longer ($p<0.01$) than ipsilateral push-off (400 ± 40 ms). Furthermore, the ipsilateral leg was mainly used at the beginning of the dive to increase the SW of the goalkeepers (Figure 3.2), and it could

not start contributing until it was back on the ground and able to apply force (Figure 3.3). The maximum SW values reached corresponded with the moment that the ipsilateral foot was back on the ground and ready to start contributing positively to the COM velocity.

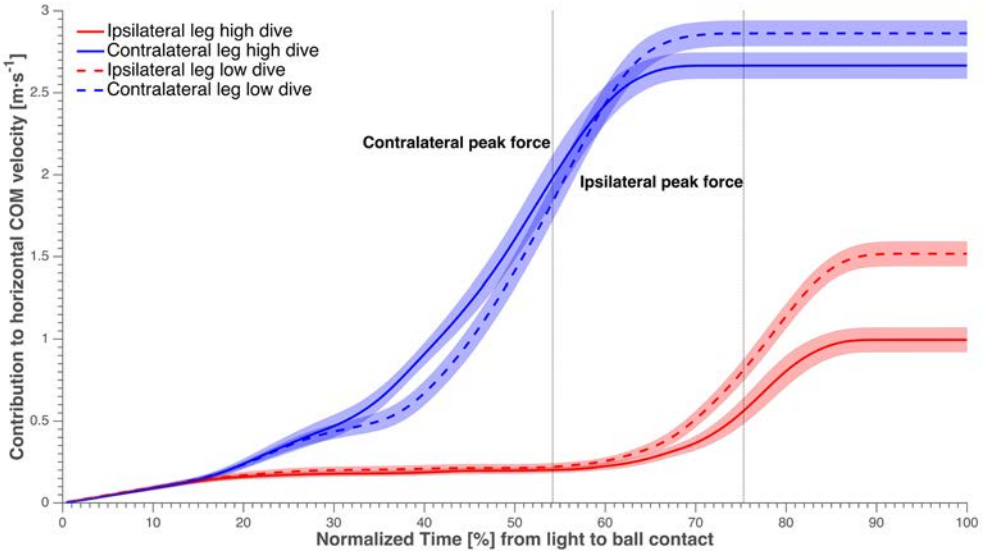

Figure 3.7. The contribution of each leg to horizontal COM velocity averaged over subjects and sides, in solid and dashed lines (refer to the figure legend), normalised over time from light to ball contact, and the standard error in shading. The time instants corresponding to maximum GRF for the contralateral and ipsilateral leg were highlighted.

The relatively wide SW reached before IPF might be beneficial for putting the contralateral leg in a better position for push-off and putting the body in a better position for generation of angular momentum. The push-off angles formed by GRF vectors of each leg with the CoP-ball vector at CPF and IPF separately, showed a better alignment for the contralateral leg when compared to the ipsilateral leg. The GRF vector of the ipsilateral leg was more upright and therefore more suitable for vertical linear momentum, which was indeed mainly generated near IPF (Figure 3.4). However, using the ipsilateral leg to

increase SW at the beginning of the dive implied a shorter contact time for the ipsilateral push-off and caused a negative contribution to COM vertical velocity (Figure 3.6) before the ipsilateral leg was back to the ground and ready to contribute positively again. So, despite a smaller overall contribution to vertical COM velocity compared to the contralateral leg, the large and rapid increase of the ipsilateral contribution to vertical COM velocity at IPF (Figure 3.6) indicates that the ipsilateral push-off was still essential to obtain vertical momentum in the high dives. Future research could analyse the diving save performance while attempting to change the SW at the starting position. Starting from a SW closer to the maximum values that we found after the sidestep, may reduce the length of the required side step and allow the ipsilateral leg to contribute positively for a longer time.

Low dives were characterised by greater horizontal linear momentum and frontal plane angular momentum, while high dives were characterised by greater vertical linear momentum. This is partially in accordance with our second hypothesis, as horizontal linear momentum appeared to be essential for both high and low dives. Overall, the horizontal linear momentum was significantly greater ($p<0.01$) than the generated vertical linear momentum at all time events. This is evident given the fact that the horizontal space of the goal to be covered by the goalkeeper, is notably beyond the vertical one. Both dive heights required a substantial angular momentum in order to orient the body horizontally and therefore increasing the horizontal reach. Contralateral leg abduction while sidestepping with the ipsilateral leg, to increase the SW, may have been beneficial to generate the angular momentum, as the latter greatly increased around CPF (Figure 3.5).

The current goalkeeping strength and conditioning programs focus mainly on vertical strength and power movement patterns (e.g. squat exercise, squat jumps, countermovement vertical jumps). Instead, it would be beneficial if strength and conditioning coaches focus on two main findings of this study: the strong contralateral leg contribution to total COM velocity, and the greater horizontal linear momentum. Thus, emphasizing lateral movement patterns in the frontal plane driven by the contralateral leg (e.g. side push-offs, lateral jumps, side lunge exercise) for physical performance testing and training, instead of the vertical movement patterns in the sagittal plane. This would be advantageous, as the two skills are relatively independent of one another and represent different leg strength/power abilities[67]. Future studies can give more insight into joint power and work to give comprehensive directions for coaches regarding isolated and coordinated joint movement training for goalkeepers.

Conclusion

In conclusion, goalkeepers start the dive by pushing-off with their contralateral leg, while increasing the SW by sidestepping with the ipsilateral leg towards the ball. Once the maximal SW is reached, the contralateral GRF tends to fall and the ipsilateral GRF starts to build-up and take over the dive. Strength and conditioning coaches need to highlight horizontal lateral skills, to both sides of the body, with emphasis on the push-off with the contralateral leg, for effective assessment and training.

Disclosure of interest

The authors report no conflicts of interest.

CHAPTER IV

Mechanics of Goalkeeper's Diving Save in Football: Training Guidelines for Physical and Technical Coaches

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Under Review

Abstract

Lower extremity joints powers, moments and angular velocities, were investigated in seven elite goalkeepers diving to save balls, shot from a ball canon to unanticipated heights (high and low) and sides (right and left). Our result showed that there was a proximal-to-distal sequence for each leg in timing of peak joints powers ($p<0.05$). Hip extensors produced the largest ($p<0.05$) peak moment, the contralateral (relative to dive side) peak was significantly larger than the ipsilateral one for high (4.56 ± 1.02 $N{\cdot}m{\cdot}kg^{-1}$, and 3.52 ± 0.79 $N{\cdot}m{\cdot}kg^{-1}$) and low dives (3.52 ± 0.79 $N{\cdot}m{\cdot}kg^{-1}$, and 2.52 ± 0.56 $N{\cdot}m{\cdot}kg^{-1}$). The ankle plantar flexors produced the second largest peak moment ($p<0.05$), with no significant difference between legs during high (2.75 ± 0.74 $N{\cdot}m{\cdot}kg^{-1}$, and 2.63 ± 0.31 $N{\cdot}m{\cdot}kg^{-1}$) and low dives (1.98 ± 0.66 $N{\cdot}m{\cdot}kg^{-1}$, and 1.94 ± 0.24 $N{\cdot}m{\cdot}kg^{-1}$). The peak ipsilateral ankle power and angular velocity were the largest ($p<0.05$) of all joints, during high (1502 ± 338 W, and 844 ± 78 $°{\cdot}s^{-1}$) and low dives (868 ± 263 W, and 810 ± 177 $°{\cdot}s^{-1}$). During high dives, total peak power of the ipsilateral leg (2294 ± 273 W) was significantly larger than of the contralateral leg (1846 ± 292 W). However, there was no difference between legs during low dives (1536 ± 291 W, and 1643 ± 326 W). Strength and conditioning coaches need to focus on hip extensors and ankle plantar flexors, and for specificity in power training that should elicit triple extension of the lower limbs' joints in a proximal to distal sequence.

Keywords:

Biomechanics; proximal-to-distal; joint power; joint moment; strength and conditioning coach; sports performance

Introduction

Goalkeepers in football have the most specialized role in their team. Their actions require timed and explosive adjustments of body speed, position and orientation in response to a stimulus. One of their most critical tasks is defending the goal during a penalty shot, which is usually performed as a diving save. Previous biomechanical studies on goalkeepers' diving saves were performed only in a laboratory set-up, simulating as much as possible the penalty situation in a football game[49,87,90]. Although, the findings of these studies were useful to the strength and conditioning (S&C), and technical coaches; more detail on the mechanics of the dive is needed to develop guidelines for training of goalkeepers.

Lower body power, defined as joint moments times joint angular velocity, summed over lower body joints, is considered by many to be an important determinant of performance in sports that require the triple extension, which is extension of the hips, knees and ankles[46,47,71,108]. In addition, optimal training for the development of lower body power should adhere to the principle of specificity, which means that to maximize transfer, the exercises chosen should show similarities to the task itself in aspects such as musculature involved, movement pattern, movement velocity, and range of motion[85]. Therefore, the first aim of this study was to analyse lower body joint powers, moments and angular velocities, along with lower limb joints coordination pattern during the diving save. This might allow recommendations for technical, and S&C coaches, who seek to enhance goalkeepers' performance. Previous papers on the diving save[87,90] used balls hanging off the high post, thus directly beside the goalkeeper above the goal line. The main

limitation of such a set-up is that it requires the goalkeepers to dive sideward, while they usually prefer to dive diagonally (sideward and slightly forward) in real game situations. This allows them to reach the ball at a better angle and effectively reduce the goal area that they need to cover. The experimental set-up in the study by Ibrahim et al. (2018) was improved by hanging the balls in front of the goal line (3D hanging ball set-up), thus allowing the goalkeeper to perform a close to natural dive. However, ecological validity was still compromised in these, because in reality the ball travels towards the goal. We therefore strived to improve upon previous studies by examining the diving save in a more realistic set-up, by using a custom made ball canon.

During high dives, the goalkeeper has a longer and more vertically directed path to be travelled than during low dives, thus we hypothesized that peak power to be larger in high than low dives. A proximal-to-distal sequence in lower body joints is usually found in most jumping and sprinting sports movements, which involve triple extension of these joints[11,18,50]. Therefore, it was hypothesized that the goalkeeper generates joints power during the dive in a proximal-to-distal sequence in each leg. Finally, because of the main frontal plane nature of the diving save, hip abduction/adduction was hypothesized to be an important contributor to the diving save performance.

Methods

Seven elite football goalkeepers, mean ± standard deviation age 18.9 ± 3 years, mass 84.9 ± 8.1 kg, height 186.5 ± 2.1 cm, and dominant leg 6 right and 1 left, participated in this study. The participants' level, at the time of the experiment, was as follows:

two goalkeepers competed in the Dutch Eredivisie (the highest level of competition nationally), three goalkeepers in the Dutch Eerste Divisie (the second highest level of competition nationally), and two goalkeepers in the Dutch under-17 Eredivisie (the highest level of competition nationally for players under 17 years of age). Before performing the experiment participants, or their parents, signed an informed consent form. For each participant, anthropometric measurements, age and injury history were gathered. Participants had not suffered from any injury that prevented them from performing the diving save at their maximum power or caused them to change their movement pattern at the time of the experiment. The experiments were conducted at the Adidas miCoach Performance Centre of AFC Ajax. The Ethics Committee of the Faculty of Behavioral and Movement Sciences of the Vrije Universiteit Amsterdam had approved the research protocol.

Data Collection and Pre-processing

Before starting the measurement, the participants performed a goalkeeper specific warm-up routine with their coaches and around 8 diving saves to get familiar with the experimental set-up. Each participant was then instructed to react and dive as fast as possible to save the ball that was being shot by a ball canon. The ball canon was placed at the penalty mark, the front-end was covered with a very lightweight striped curtain, in order to prevent any anticipation of ball height and side. The ball canon was calibrated for the goal corners before every subject, and was not displaced during the whole measurement. The set ball speed was calculated to allow the ball to reach the goal in 1.2 ± 0.1 s, in accordance with the result of a recent study on total dive time (reaction time + dive movement time) by Ibrahim

et al. (2018). A passive marker motion analysis system (Vicon 612, Oxford UK) was used after calibration with an active wand comprising 5 markers. The system consisted of 10 infrared cameras and it was used to capture, at 200 Hz, 3D coordinates data of 44 markers. Markers were attached to different body segments in the form of clusters (feet, shanks, pelvis, thorax, head and forearms), the thighs were modelled between the shanks and pelvis, and the upper arms were modelled between the thorax and forearms, in order to obtain a full-body model without occlusion of the markers during the trials and limiting the risk of landing on markers. The markers were attached in a well-recognizable pattern to facilitate the labelling with Vicon Nexus Software (version 1.8.5). Soft markers were used on areas that are prone to impact at landing. Anatomical coordinate systems of the segments were marked with single markers and related to the corresponding marker clusters during a measurement in a reference position (T-pose). Details of the 3-D inverse dynamics model that was used in this study can be found elsewhere[31,32,48,55].

Two custom-made strain-gauge, 1x1 m, force plates (Vrije Universiteit Amsterdam, Amsterdam, The Netherlands) were used to measure ground reaction forces (GRF) produced by each leg separately at a rate of 1000 Hz. Each force plate was separately covered by artificial football grass, to prevent any force transfer between force plates. A mattress was placed beside each force plate, to avoid unevenness of the floor level, and to keep the goalkeeper and the marker set-up safe at each landing. Two Basler high-speed video cameras (50 Hz) were used to record all trials in the frontal plane for visual checks and for detection of ball contact.

Data Analysis

All kinematic and kinetic analyses were carried out using custom software in MATLAB (R2015b, MathWorks inc, US). Kinematics signals were low pass filtered with a 12 Hz cut-off frequency. Timing variables were defined relative to the onset of the dive, which was detected using an algorithm based on the Approximated Generalized Likelihood-Ratio[89] (AGLR). AGLR was successfully used before for detecting the onset of the dive towards hanging balls[49]. It works by (1) detecting the alarm time (the time instant when the signal reaches the pre-set threshold) using a sliding test window, then (2) tracking back the signal to detect the initial change time using Maximum Likelihood techniques[75]. We used a threshold equal to 20% of the goalkeeper's body weight, and three different input signals (i.e. total horizontal GRF, total vertical GRF, and Vertical GRF of the contralateral leg (the leg opposite to the diving side). The dive onset was defined as the average of the two out of three onsets, having the smallest mutual difference.

The instant of contralateral (CPF) and ipsilateral peak force (IPF) were defined as the instants when the contralateral and ipsilateral leg exerted their maximum resultant GRF, respectively. Take-off was defined as the instant that the vertical component of GRF, summed over legs, dropped below 10% body weight and ball contact as the first frame when contact took place between the ball and the goalkeeper, as detected from the high-speed cameras.

Total body linear momentum in the vertical and horizontal direction towards the ball, and frontal plane angular momentum time series were calculated[104] from the detected movement onset to ball contact. The angular velocities of lower body joints

(hips, knees and ankles) were calculated by first expressing the rotation matrix of the distal segment relative to the proximal one and then using the equation of Berme and Capozzo (1990). Positions of the centres of mass and the moments of inertia were estimated according to Zatsiorsky (2002). Kinematics of the body segments were used together with the GRFs to calculate moments at the ankles, knees and hips, in a bottom-up dynamic linked segment model[55]. To obtain the 3D components of the net moments, the ankle moments were projected onto the foot coordinate system (CS), the knee moments were projected onto the shank CS, and the hip moments were projected onto the thigh CS. Hip, knee and ankle powers were calculated by scalar multiplication of angular velocity and moment of the concerned joint. Total body power was calculated by taking the derivative of the total body energy, which is the sum of 3D potential, and linear and angular kinetic energies over all segments, ignoring the hands.

Hip joint angles were defined as the Euler angles of the thigh to the pelvis anatomical coordinate systems. The sequence of rotation was: flexion-extension, external-internal rotation and abduction-adduction[102].

Statistical Analysis

All time series were time-normalized (NT) from the detected movement onset to ball contact. All data are presented as mean ± standard deviation. Peak magnitudes, and absolute values at CPF and IPF of the time series were compared between heights and sides, and between heights, and contralateral and ipsilateral legs, with two-way repeated measures ANOVAs. Significant interactions were further explored by paired t-tests.

The timing of peak joints power was compared between joint plane, height and side with three-way repeated measures ANOVAs. Also, the timing and magnitude of peak joints power, the magnitude of peak net joints moment and of peak joints angular velocity were compared between height, diving side, and leg side. If the results of three-way ANOVA showed a significant main effect for joints, planned comparisons were used to identify between which specific joints the timing of peak power differed significantly from the nearby peak in another joint. All statistical analyses were carried out using IBM SPSS Statistics 20.

Results

Repeated measures ANOVAs showed that there was a significant effect ($p<0.01$) of dive height on all GRF, linear and angular momentum variables, except peak horizontal GRF of the ipsilateral and contralateral leg (Table 4.1). However, there was no main effect of dive side (all $p>0.093$), and no interaction with dive side on any of the variables analysed.

The total body power produced by the goalkeeper was significantly larger during high dives than during low dives which confirms our first hypothesis ($p<0.01$). As for the total power per leg (ipsilateral vs contralateral leg), there was a significant interaction between diving height and leg side ($p<0.05$). During high dives, the peak power generated by the ipsilateral leg (2294 ± 273 W) was significantly greater ($p<0.05$) than the contralateral leg (1846 ± 292 W). However, there was no significant difference between the peak powers generated by the ipsilateral (1536 ± 291 W) and contralateral (1643 ± 326 W) legs during low dives.

Table 4.1. Peak magnitudes of the variables listed during high and low left and right diving saves in response to canon ball shot. Significant main effects are indicated (** p<0.01). No significant interactions between height and side were found.

Variable	High dive Left	High dive Right	Low dive Left	Low dive Right	Mean difference High – Low	Mean difference Left – Right
Peak vertical linear momentum [kg·m·s^{-1}]	101 ±27	116 ±23	16 ±13	22 ±15	+90**	-10
Peak horizontal linear momentum [kg·m·s^{-1}]	324 ±51	315 ±46	340 ±48	344 ±47	-23**	3
Peak angular momentum (frontal plane) [kg·m^2·s^{-1}]	37 ±6	36 ±5	48 ±9	47 ±9	-11**	1
Peak ipsilateral GRF vertical [N]	1303 ±190	1382 ±178	888 ±134	963 ±165	+417**	-77
Peak contralateral GRF vertical [N]	1542 ±311	1483 ±243	1308 ±244	1295 ±298	+211**	36
Peak ipsilateral GRF horizontal [N]	502 ±128	479 ±105	484 ±101	497 ±81	0	5
Peak contralateral GRF horizontal [N]	850 ±207	880 ±163	802 ±143	804 ±224	62	-16
Total body power [W]	3345 ±810	3538 ±470	2574 ±585	3001 ±704	+653**	-310

Figures 4.1 and 4.2 show the time series of lower body joint powers, moments and angular velocities from dive onset to take-off, during high and low dives, respectively. The contralateral sagittal hip power was induced by a large hip extension moment, which was the largest joint moment of all ($p<0.05$). However, the ipsilateral sagittal hip power was characterized by a large area under the curve, from 63% to 86% of NT. This was induced by an ipsilateral hip extension moment, which was the second largest peak of all ($p<0.05$). The peak ipsilateral ankle power in the sagittal plane was significantly greater than all the other analysed joint powers. It was induced by the fourth largest joint moment (ipsilateral ankle plantar-flexion moment), with the third largest being also plantar flexion but of the contralateral

ankle ($p<0.05$).

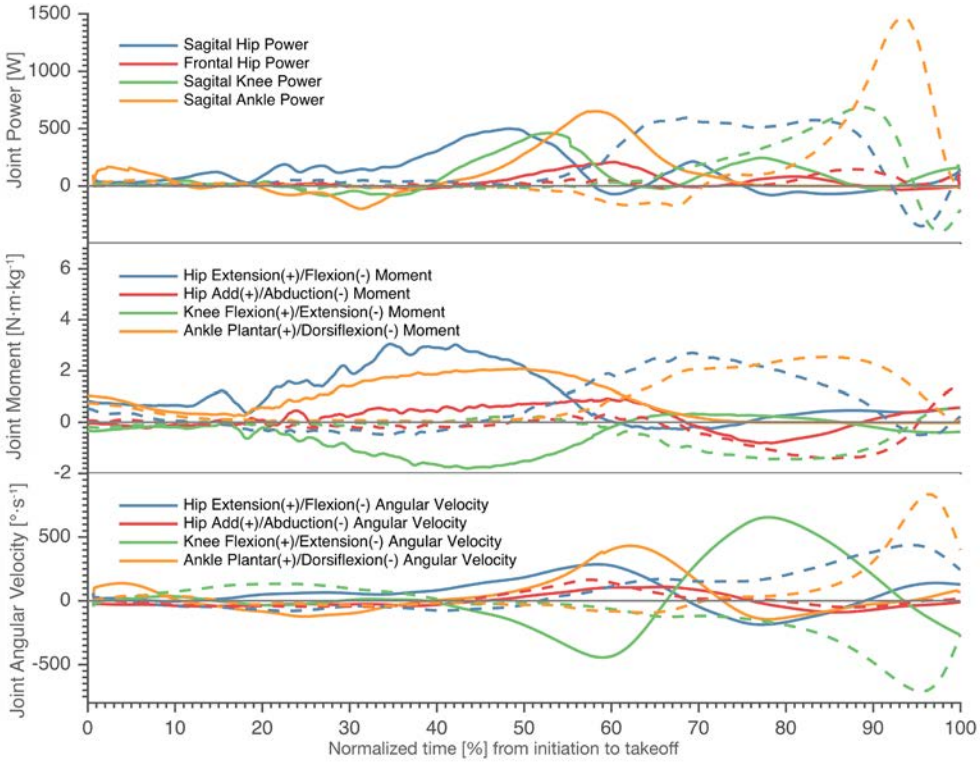

Figure 4.1. Time series averaged over subjects, for joints powers (top), joints moments (middle), and joints angular velocities (bottom), of goalkeepers diving to save high balls. Solid lines correspond to the contralateral leg, and the dashed lines to the ipsilateral leg. The x-axis is the normalized time.

Repeated measures ANOVA showed a significant effect of joint on timing of peak powers ($p<0.001$), with no significant effect for dive side or height. Largely in line with the hypothesised proximo-distal sequence, pairwise comparisons showed that the sequence of lower limbs peak joints power consisted of 5 main events (Table 4.2, Figure 4.3): (1) peak contralateral hip power in the sagittal plane, (2) peak contralateral knee power in the sagittal plane, peak contralateral ankle power in the sagittal plane, peak contralateral hip power in the frontal

plane, (3) peak ipsilateral hip power in the sagittal plane, and in the frontal plane, (4) peak ipsilateral knee power in the sagittal plane, and (5) peak ipsilateral ankle power in the sagittal plane. The timing of each event number (1 to 5) was significantly different from the timing of the previous and the next event number.

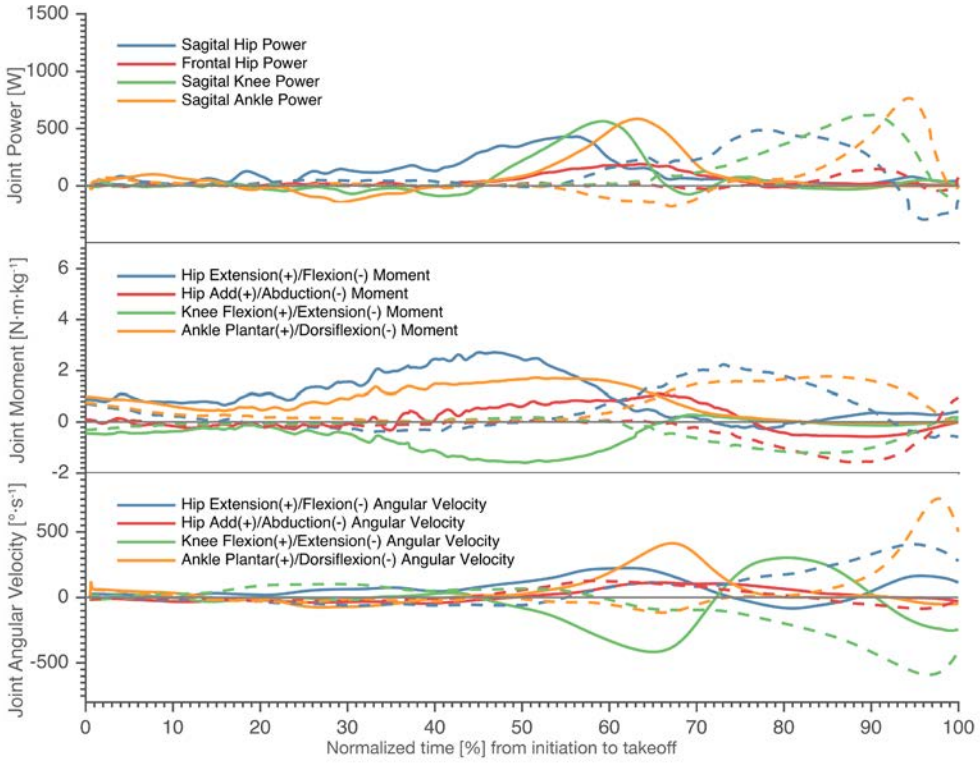

Figure 4.2. Time series, averaged over subjects, for joints powers (top), joints moments (middle), and joints angular velocities (bottom), of goalkeepers diving to save low balls. Solid lines correspond to the contralateral leg, and the dashed lines to the ipsilateral leg. The x-axis is the normalized time.

Table 4.2. Timing and Magnitudes of peak joint power, along with the underlying magnitudes of peak net joint moment and angular velocity, and statistical results of three-way repeated measures ANOVA*. The bottom section is showing the spotted significant differences for the tested factors (dive height, dive side, and leg side / joint plane)

	Variables	HIP SAGITTAL		HIP FRONTAL		KNEE SAGITTAL		ANKLE SAGITTAL	
		Contra-lateral	Ipsi-lateral	Contra-lateral	Ipsi-lateral	Contra-lateral	Ipsi-lateral	Contra-lateral	Ipsi-lateral
High Dives	Timing of peak joint power [% of NT]	46 ±12	74 ±9	62 ±11	77 ±26	59 ±13	87 ±3	60 ±4	93 ±0.5
	Peak joint power [W]	787 ±220	860 ±259	305 ±122	360 ±284	617 ±231	727 ±258	837 ±174	1502 ±338
	Peak net joint moment [N·m·kg^{-1}]	4.56 ±1.02	3.71 ±0.62	2.11 ±0.79	1.51 ±0.38	2.22 ±0.8	1.56 ±0.49	2.75 ±0.74	2.63 ±0.31
	Peak joint angular velocity [°·s^{-1}]	322 ±80	462 ±79	180 ±42	138 ±84	543 ±89	723 ±75	558 ±111	844 ±78
Low Dives	Timing of peak joint power [% of NT]	53 ±9	77 ±5	64 ±9	93 ±11	62 ±10	89 ±2	64 ±6	94 ±1
	Peak joint power [W]	656 ±275	605 ±181	318 ±113	284 ±210	543 ±399	668 ±229	658 ±251	868 ±263
	Peak net joint moment [N·m·kg^{-1}]	3.52 ±0.79	2.52 ±0.56	1.81 ±0.68	1.81 ±0.29	1.76 ±0.71	1.32 ±0.28	1.98 ±0.66	1.94 ±0.24
	Peak joint angular velocity [°·s^{-1}]	297 ±92	425 ±92	185 ±30	148 ±132	537 ±136	613 ±107	480 ±171	810 ±177
Significant differences	Peak Power	High > Low		None		None		Ipsi > Contra High > Low	
	Peak net joint moment	Contra > Ipsi High > Low		None		Contra > Ipsi		High > Low	
	Peak joint angular velocity	Ipsi > Contra High > Low		None		Ipsi > Contra		Ipsi > Contra	
	sequence (1-5)	(1)	(3.a)	(2.c)	(3.b)	(2.a)	(4)	(2.b)	(5)

**There was no two-way or three-way interactions*

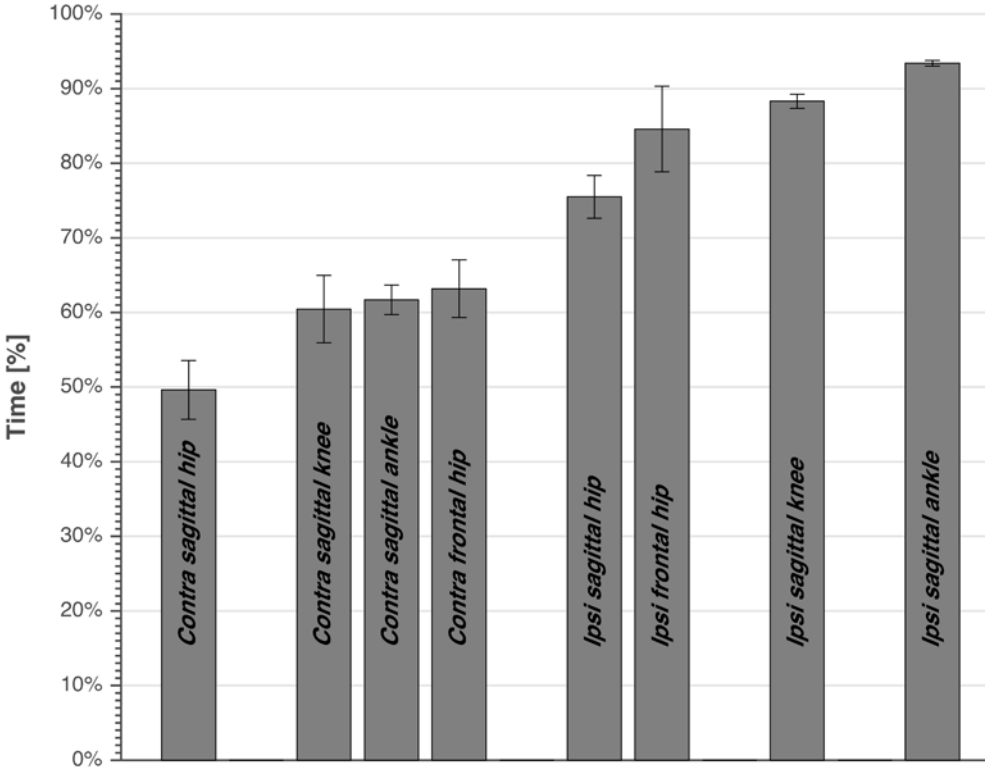

Figure 4.3. The timing of peak joints power averaged over subjects, side and height, expressed as percentage of total time from dive-onset to takeoff. Standard error is also presented. The bars are grouped, and each joint power of a group is significantly different than the other members of other groups.

Discussion

The current study was the first to attempt analysing the biomechanics of goalkeeper's diving save in football, while simulating the penalty diving save as realistic as possible.

In accordance with our first hypothesis, the total body power produced by the goalkeeper was significantly greater during high dives than during low dives. This difference was somehow expected, given the larger vertical path that needs

to be covered in high dives. The analysis of peak power per leg, showed there was no significant difference between legs when diving to save low balls. In contrast, the peak ipsilateral power was greater than the contralateral one when diving to save high balls. However, this does not mean that the ipsilateral leg contributed more to the COM velocity towards the ball, as our previous study found a similar pattern in GRF but more contribution to COM velocity for the contralateral rather than the ipsilateral leg[49]. This was attributed to better orientation of the contralateral leg relative to the target, and a longer contact time which implies a longer time for application of power.

In accordance with our second hypothesis, both the contralateral and ipsilateral legs followed roughly a proximal-to-distal sequence in peak joint powers. This is in agreement with findings of Chiu et al. (2014), analysing lower limb coordination in a vertical jump task. They found that a proximal-to-distal sequence allows the athlete to generate larger hip extensor, knee extensor and ankle plantar flexor net joint moments, resulting in larger angular accelerations and pelvis linear acceleration. It was also suggested that, if net joint moments of hip and knee extensors occur concurrently, this may result in antagonist co-contraction at the knee, resulting in slower joint angular accelerations and slower pelvis linear acceleration. After analysing the sequence in peak joints powers, we identified five main events in the diving save (Table 4.2, Figure 4.3). The timing of the identified 5 events of peak joints power were significantly different from each other, however during the second event several joints reached their peaks sequentially but without a significant difference in timing. The peak contralateral ankle power in the sagittal plane (2.b; Table 4.2) occurred non-significantly after the peak contralateral

knee power in the sagittal plane (2.a; Table 4.2). In addition, the peak contralateral hip power in the frontal plane (2.c; Table 4.2) was unexpectedly the last peak for the contralateral leg, and the only joint rotation that did not respect the proximal-to-distal sequence. The latter is maybe due to the fact that the movement of the contralateral leg looks like a sidestep cut more than a push-off for jumping. Given that joint coordination in the diving save follows, except for the contralateral hip abduction, a proximal-to-distal sequence, a high distal angular velocity and joint power can be produced at limited shortening velocity of muscles, which reduces the required muscle activation. A proximal-to-distal sequence, described by the kinetic link principle or otherwise known as the summation of speed principle[64,78], seems to be the most adapted lower body / upper body coordination pattern in explosive sports skills[12,18,98,99]. Less empirical evidence still supports the other coordination pattern described by the principle of optimal coordination of partial momenta and characterised by simultaneous timing in peak joints angular velocities at the instant of push-off/kick/release, while all related joints are fully extended[23,78].

The two largest joint moments during the diving save, were the contralateral hip extension as first, and the ipsilateral hip extension as second. Contralateral hip extensors generated significantly greater joint moments than ipsilateral hip extensors, during high and low dives. The powers generated by contralateral and ipsilateral hip extensors were not the highest of all joints. This may be due to the fact that the hip is initiating the diving save by rotating large and heavy segments (trunk, pelvis, and thighs), which makes it hard to reach high angular velocities. The large net hip moment indicates the importance of training hip extensor muscles, and most importantly the hip

extensors of the contralateral leg during a push-off movement pattern. Hip extensors can also be trained with resistance exercises such as deadlift, sumo deadlift[28], squat and sumo squat[83]. These exercises can be performed without any position modification given that hip angles in the transversal and frontal planes were almost neutral, during the current study, at peak power instant in the diving save.

Ankle plantar flexion moments were the second largest after hip extension. The contralateral ankle produced a similar plantar flexion moment compared to the ipsilateral ankle, during high and low dives. However, the peak power of the ipsilateral leg was greater than of the contralateral leg during both dive heights. The contralateral leg always started the motion from a static position, while the ipsilateral leg started the actions after a side step and push-off with the contralateral leg. Therefore, it may be less problematic to attain high peak angular velocities for the ipsilateral leg than for the contralateral leg, because the ipsilateral ankle can take benefit of the pelvis horizontal linear velocity and the stretch-shortening cycle.

The knee extension and hip abduction/adduction moments were lowest, which suggests that they are not limiting factors in the diving save. This contradicts our third hypothesis, which was based on the finding that the horizontal component of the push-off force was larger than the vertical component[49]. However, in the current study we showed that this horizontal COM velocity was mainly produced by the hip extensors and ankle plantar-flexors, instead of hip add/abductors, which is possible because the body is laterally inclined toward the diving side.

One of the limitations of the current study, was the use of

mattresses on the landing area, on both sides of the goal. However, the mattresses were necessary to make the floor level even with the force plates, and they were used to keep the goalkeeper and the marker set-up safe at each landing. It was also believed that the presence of mattresses would not affect performance or the diving save pattern, instead it would allow the goalkeeper to dive comfortably without worrying about the landing and the marker set-up.

In a previous study with hanging balls instead of a ball canon, we suggested that S&C coaches, and technical coaches need to highlight horizontal lateral skills, to both sides of the body, with emphasis on the push-off with the contralateral leg[49]. In part, this was based on the finding that, in the diving save, there is a strong contralateral leg contribution to total COM velocity, and a large horizontal linear momentum. In the current study, we have found that the large horizontal linear momentum and horizontal COM velocity were generated mainly by the hip extensors and ankle plantar flexors. While this initially seems to contradict the above-mentioned focus on the lateral skills, it should be stressed that asymmetry of ipsi- and contralateral leg flexion-extension power can result in major lateral motions. The analysis of hip abduction/adduction angle, and hip external/internal rotation angle at the instant of maximum hip extension power, revealed that this near to oblique body orientation is not created by major joint movements in the frontal or transverse planes. Instead, it may be created by a total body angular momentum, from the contralateral push-off and ipsilateral sidestep. When a segment is moving in a certain velocity (i.e. the ipsilateral leg during the sidestep), if the distal-end of the segment suddenly stops moving (i.e. the ipsilateral foot lands and start to push-off), then an angular momentum

in the direction of the movement is created around the distal-end of the segment (i.e. centre of rotation).

We conclude that S&C coaches may optimize their training sessions if they include power exercises loaded in the sagittal plane, with a proximal-to-distal sequence in lower extremity joints. These power exercises need to focus on hip drive (hip extension power) and they need to involve a transfer in the kinetic energy developed from the lower to the upper body by reaching overhead to save the ball. Olympic weightlifting exercises have been found to simulate the above conditions[9,19,38,39,56,92].

The kinetic results and the recommendations of the current study need to be combined with the kinematic results and recommendations of our previous study[49], for optimal training design. Power exercises focusing on triple extension of lower body joints (e.g. power clean and hang power clean, power snatch and hang power snatch, and push jerk) need to be included in the training of goalkeepers diving save, along with lateral movement patterns in the frontal plane driven by the contralateral leg (e.g. side push-offs, lateral jumps, side lunge exercise). Future intervention studies can confirm the effect of the above training recommendations along with the ones from our previous study[49], on goalkeeper's dive time.

Conclusion

In conclusion, goalkeepers perform the diving save using a proximal-to-distal sequence in lower extremity peak joint powers. The main muscles involved in the push-off are the hip extensors and ankle plantar flexors. No differences were found between left and right dives. The timing of peak power was

similar between high and low dives, while the magnitude of joint powers was smaller in low than in high dives. Peak total power for the ipsilateral leg was larger than the contralateral leg during high dives, but there was no difference during low dives. These findings can be used to improve prescriptions of technical and strength training for goalkeepers.

Disclosure Statement

No potential conflict of interest was reported by the authors.

CHAPTER V

The Effect of Preparatory Posture on Goalkeeper's Diving Save Performance in Football

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Under Review

Abstract

The aim of this study was to investigate whether self-selected knee angle and stance width are optimal in elite football goalkeepers diving to save high and low balls at both sides of the goal. 3D kinetics and kinematics were measured in ten goalkeepers while performing diving saves to unanticipated ball positions. Goalkeepers performed dives from preferred and imposed preparatory posture, by altering knee angle (45°, 75° and 90°) or stance width (50%, 75% and 100% of leg length) independently at the starting position. Diving saves from goalkeeper's preferred preparatory posture were performed before and after the imposed conditions, PT1 and PT2 respectively. Our results showed that goalkeepers dived from SW75 and saved the ball non-significantly faster than from PT2 (attributed to a learning effect) and significantly faster ($p<0.05$) than in all other conditions. The goalkeepers Centre of Mass (COM) travelled a larger distance between contralateral and ipsilateral push-offs, from SW75 than PT1 (+9 cm horizontally $p<0.01$ and +5 cm vertically $p<0.05$ for high dives; +12 cm horizontally $p<0.01$ for low dives) and PT2 (+5 cm horizontally $p<0.01$ and +5 cm vertically $p<0.01$ for high dives; +9 cm horizontally $p<0.05$ for low dives). The goalkeepers were also more efficient in the dive, as smaller countermovements were observed during high dives from SW75 than PT1 (-6 cm $p<0.01$) and PT2 (-4 cm $p<0.05$), and less variation in vertical COM velocity occurred during low dives from SW75 than PT1 (-0.2 $m \cdot s^{-1}$ $p<0.05$) and PT2 (-0.2 $m \cdot s^{-1}$ $p<0.05$).

Keywords:

Countermovement; stance width; centre of mass; joint power; strength and conditioning coach; sports performance

Introduction

When athletes prepare to perform an explosive movement, they set themselves in a specific preparatory posture, often referred to as the power position. This position is assumed to allow optimal development of joint torques to generate the appropriate motor response to a stimulus. Slater-Hammel (1953) investigated the effect of preparatory posture on reaction times in placing the correct leg (left or right leg) diagonally forward in response to a light signal. Standing with the weight equally distributed over flat feet resulted in faster reaction times than standing on the ball of the feet. Loockerman (1973) investigated the optimal preparatory posture in tennis, and found that a narrow stance width (SW) resulted in the quickest reaction time. However, Hopkins (1984) found that a wide SW allowed the tennis player to recover faster from a forehand to a backhand, than narrow SW. The effect of preparatory posture on movement time was also studied in the literature, as it may allow for more improvement than reaction time. Yamamoto (1996) studied the influence on execution of trunk rotation movements of preparatory postures with knee and hip flexion angles varying from full extension, slight flexion, deep flexion and subjects' preferred position. Slightly bending the knees and hips, at approximately 24° each, resulted in faster reaction and movement times. Finally, Ball and Giblin (2009) investigated the effect of SW in field hockey goalkeepers performing one save for each corner of the goal for each of ten different conditions, at preferred SW and instructed SW ranging from 0.4 m to 1.2 m. They found that wide SW (1.1 m), wider than their preferred SW, was optimal for eight out of ten goalkeepers, as movement times were faster compared to narrower and preferred SW.

Football is characterized by a low number of goals scored during a match, which means that minor mistakes or under-performance of the goalkeeper can make the team lose the game. During the penalty shot, the ball reaches the goal in about 600 ms, faster than the movement times of goalkeepers' dives[49,66], which average about 1000 ms. Therefore, minimization of the movement time of the dive could greatly enhance performance. Observation of video analysis of over 100 diving saves revealed large variability in preparatory postures between goalkeepers (unpublished data) and it is unclear whether self-selected postures are optimal. Therefore, the aim of this study was to independently vary the SW and knee angle in the preparatory posture of elite goalkeepers and to analyze the effects on the performance of the goalkeepers' diving saves. Based on the previous findings in field hockey, we hypothesized that goalkeepers in football would dive faster if standing with a relatively wide SW.

Methods

Ten elite football goalkeepers, mean ± standard deviation age 18.4 ± 2.6 years, mass 82.6 ± 9.1 kg, height 186 ± 2.4 cm, and dominant leg 9 right and 1 left, participated in this study. The participants' level, at the time of the experiment, was as follows: two goalkeepers in the Dutch Eredevisie (the highest level of competition nationally), six goalkeepers in the Dutch Eerste Divisie (the second highest level of competition nationally), and two goalkeepers in the Dutch under-17 Eredevisie (the highest level of competition nationally for players under 17 years of age). Before performing the experiment participants, or their parents, signed an informed consent form. For each participant, anthropometric measurements, age and injury

history were gathered. Participants had not suffered any injury that prevented them from performing the diving save at their maximum power or that caused them to change their movement pattern at the time of the experiment. The experiments were conducted at the Adidas miCoach Performance Centre of AFC Ajax. The Ethics Committee of the Faculty of Behavioral and Movement Sciences of the Vrije Universiteit Amsterdam had approved the research protocol.

Data collection and pre-processing

The experimental set-up, data collection and pre-processing are described in details in the third chapter. Briefly, trajectory data from 44 markers attached to the goalkeepers, were captured using 10 infrared cameras at 200 samples/s (Vicon 612, Oxford UK) during a diving save to save high (190 cm) and low (30 cm) hanged balls. Ground reaction forces (GRF) produced by each leg were measured separately at a rate of 1000 samples/s with two custom-made strain-gauge based force plates (Vrije Universiteit Amsterdam, Amsterdam, The Netherlands). In addition to measuring goalkeeper's diving saves from their own preferred preparatory postures, they also dived from imposed preparatory postures. Knee flexion angle (KA) was manipulated during the preparatory posture, using a goniometer and by imposing three different conditions: 45° (KA45), 75° (KA75) and 90° (KA90). Stance Width (SW) was also manipulated during the preparatory posture, by normalizing SW to personal leg length and imposing three different conditions with feet positions indicated with tape on the force plates: 50% leg length (SW50), 75% leg length (SW75) and 100% of leg length (SW100). When knee flexion angle was manipulated, SW was left to the goalkeeper's choice,

and vice-versa.

The experiment protocol was performed in the following order: (1) 5 successful dives using goalkeepers' own preferred preparatory postures (PT1), randomized over side and height of the dive, (2) 24 successful dives in total, randomized over side, height and technique (KA45, KA75, KA90, SW50, SW75, SW100), and (3) 5 successful dives using goalkeepers' own preferred preparatory postures (PT2), randomized over side and height of the dive. Section 3 of the experimental protocol was included to take potential learning effects during the measurements into account. The goalkeepers performed a total of 34 dives with 1-minute recovery time between dives.

Data analysis

All kinematic and kinetic analyses were carried out using custom software in MATLAB (R2015b, MathWorks inc. US). Six time instants were identified for the diving save: Light signal, dive onset, contralateral peak force (CPF), ipsilateral peak force (IPF), take-off and ball contact.

Methods for detecting the dive onset are also given in details in the third chapter. Briefly, we detected the dive onset using an algorithm based on the Approximated Generalized Likelihood-ratio[89] (AGLR). It works by (1) detecting the alarm time (the time instant when the signal reaches the pre-set threshold) using a sliding test window, then (2) tracking back the signal to detect the initial change time using Maximum Likelihood techniques[75]. We used a threshold equal to 20% of goalkeeper bodyweight, and three different input signals (i.e. total horizontal GRF, total vertical GRF and Vertical GRF of the contralateral leg (the leg opposite to the diving side). The dive onset was defined as the

average of the two out of three onset estimates, having the smallest mutual difference.

All timing variables were defined relative to the onset of movement. The instant of contralateral peak force (CPF) and ipsilateral peak force (IPF), were defined as the instants that the contralateral and ipsilateral leg exerted their maximum resultant GRF, respectively. Contralateral and ipsilateral push-offs time periods were considered as 10 samples before and after the contralateral and ipsilateral peak forces, respectively. Take-off was defined as the instant that the vertical component of GRF, summed over legs, dropped below the 10% bodyweight threshold and ball contact as the instant that a shift in position of the ball's markers was detected in any direction.

Total dive time was calculated as the time from light signal to ball contact, then it was split into two main parts: reaction time and movement time. Reaction time was calculated from light signal to the detected dive onset, and movement time was from dive onset to ball contact.

SW was calculated as the distance between the medial malleoli and was expressed as a percentage of the participant's leg length. The leg length of each goalkeeper was measured from the palpated greater trochanter to the ground while the subject was standing on bare feet. KA was defined as the Euler angle of the shank anatomical coordinate system (ACS) relative to the thigh ACS. The sequence of decomposition was: flexion-extension, external-internal rotation and abduction-adduction[102].

Lower limbs' joint powers, horizontal and vertical positions of total body centre of mass (COM), and COM velocity in the

horizontal and vertical directions were calculated in order to explain possible differences in diving save performance. The positions and velocities of COM were analysed from the light signal to the end of the fastest dive.

The angular velocities of lower body joints (hips, knees and ankles) were calculated by first expressing the rotation matrix of the distal segment relative to the proximal one, then using the equation of Berne and Capozzo (1990). Positions of the centres of mass and the moments of inertia were estimated according to Zatsiorsky (2002). Kinematics of the body segments were used together with the GRFs to calculate moments at the ankles, knees and hips, in a bottom-up dynamic linked segment model[55]. To obtain the 3D components of the net moments, the ankle moments were projected onto the foot coordinate system (CS), the knee moments were projected onto the shank CS, and the hip moments were projected onto the thigh CS. Hips, knees and ankles power were calculated by scalar multiplication of angular velocity and moment of the concerned joint.

Statistical analysis

All time series except COM position and velocity were time-normalized from the light signal until ball contact. All data are presented as mean ± standard deviation between subjects. Dive time, reaction time and peak magnitudes of lower limbs' joints power were compared between techniques (8 levels: PT1, SW50, SW75, SW100, KA45, KA75, KA90, PT2), diving heights and sides with three-way repeated measures ANOVAs. However, after finding no effect of side on any of the variables, all the data were averaged over sides and two-way repeated

measures ANOVAs (technique and diving height) was performed and presented in this paper. Differences in starting position variables (SW and KA) were tested between PT1 and PT2 with paired t-tests, to test for any learning effect.

In case of significant effects of technique, planned comparisons were performed to find (1) significant differences between instructed techniques versus PT1 and versus PT2. Subsequently, the fastest technique was compared to all others, and the nature of differences with PT1 and PT2 was explored in more detail for the fastest technique. These comparisons helped to interpret any possible physical and/or technical differences in diving save performance between techniques. All statistical analyses were carried out using IBM SPSS Statistics 20.

Result

Two-way repeated measures ANOVA showed that there were no significant effects of technique ($p=0.68$) and height ($p=0.84$) on reaction time. Two-way repeated measures ANOVA did show a main effect of technique and height on dive time ($p<0.01$), with no interaction effect ($p=0.12$). Low dives were significantly faster than high dives ($p<0.01$). Paired t-tests between PT1 and PT2 showed that during PT2 participants adopted a SW that was significantly wider than during PT1 (47 ± 9% vs. 41 ± 5% of leg length; $p<0.01$; Figure 5.2). PT1 was significantly faster than KA90 ($p<0.05$), and non-significantly faster than KA45 ($p=0.1$) and KA75 ($p=0.11$; Table 5.1). With respect to dive time, PT1 was similar to SW50 ($p=0.93$) and SW100 ($p=0.96$), and it was significantly slower than SW75 ($p<0.05$; Table 5.1). PT2 was significantly faster than KA45 ($p<0.05$), KA75 ($p<0.01$), and KA90 ($p<0.01$; Table 5.1). Furthermore, it was non-significantly

faster than SW50 (p=0.15) and SW100 (p=0.45), and it was non-significantly slower than SW75 (p=0.69; Table 5.1).

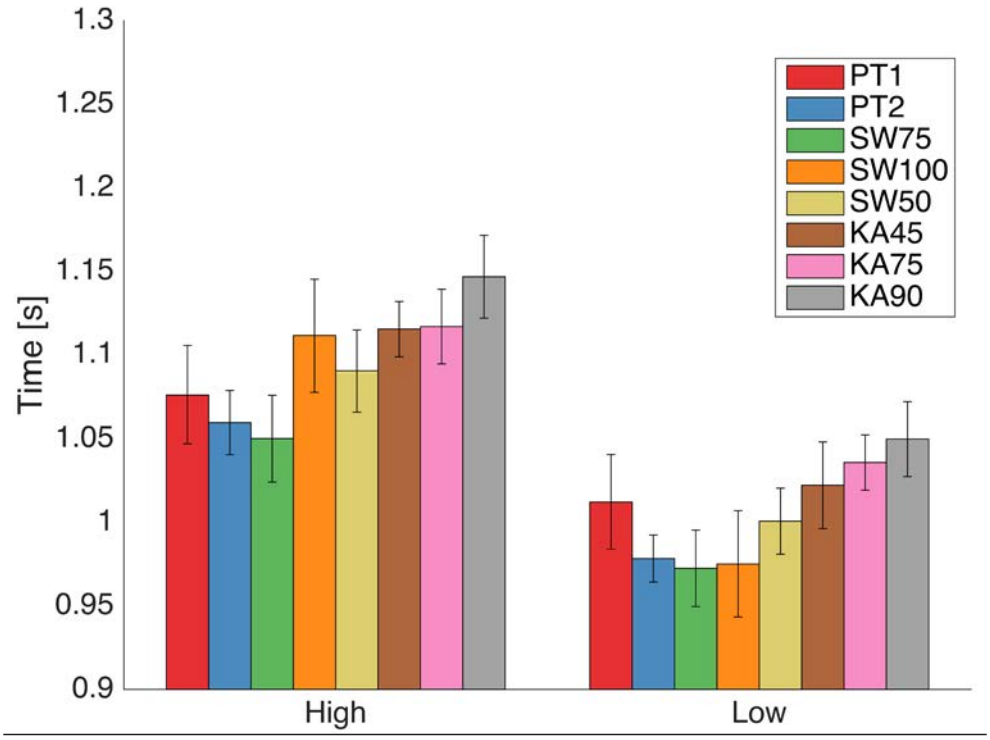

Figure 5.1. Average dive time, with standard error, from calculated movement onset to detected ball contact.

Table 5.1. Planned comparison of dive time averaged over heights, of all instructed techniques versus PT1 and versus PT2 (* p<0.05; ** p <0.01).

Technique compared to PT1/PT2	PT1 – addressed technique mean difference (standard error)	PT2 – addressed technique mean difference (standard error)
SW100	+0.001 s (0.016)	-0.024 s (0.030)
SW75	+0.033 s * (0.014)	+0.008 s (0.019)
SW50	-0.001 s (0.014)	-0.027 s (0.016)
KA45	-0.025 s (0.013)	-0.05 s * (0.020)
KA75	-0.032 s (0.018)	-0.057 s ** (0.013)
KA90	-0.054 s * (0.019)	-0.079 s ** (0.021)

The SW75 condition resulted in the fastest dive with an average of 1.05 s for high balls and 0.972 s for low balls (Figure

5.1). Planned comparisons showed that SW75 was significantly faster than all the other conditions ($p<0.05$), except PT2, which showed only a non-significantly, longer dive time than SW75 (Table 5.2). Based on the statistical results on dive times, all techniques except SW75 were similar or slower than preferred technique (PT1 and PT2). Thus, the rest of the paper will focus on analysing and explaining differences in physical and technical performances between SW75 and the preferred technique (PT1 and PT2).

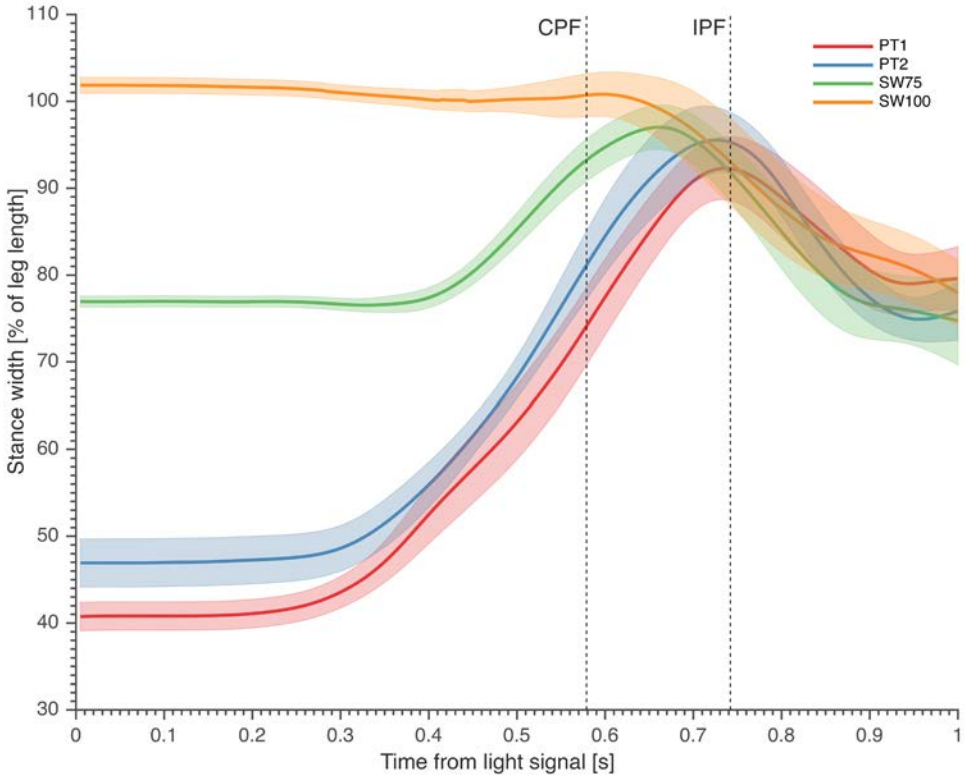

Figure 5.2. The average SW kinematics from light signal. Contralateral peak force (CPF) and ipsilateral peak force (IPF) are marked, and the standard error is indicated by the shading.

Table 5.2. Pairwise comparisons of dive time across techniques, after averaging over dive heights. (* p<0.05; ** p<0.01).

Technique compared to SW75	Mean difference (SW75 – addressed technique)	P value	95% confidence interval	
			Lower Bound	Upper Bound
PT1	-0.033 s *	0.044	-0.065	-0.001
PT2	-0.008 s	0.699	-0.052	0.037
SW100	-0.032 s *	0.038	-0.062	-0.002
SW50	-0.034 s **	0.003	-0.053	-0.016
KA45	-0.057 s **	0.001	-0.085	-0.03
KA75	-0.065 s **	0.002	-0.099	-0.031
KA90	-0.087 s **	0.001	-0.122	-0.052

Table 5.3. Peak joint powers, averaged over subjects and sides, of the contralateral and ipsilateral legs for PT1, PT2 and SW75 techniques. For each joint, the first line is for high dives and the second line is for low dives. The bold values indicate significant difference between techniques (p<0.01) and the underlined values indicate significant difference between heights (p<0.05).

Variables	Contralateral leg			Ipsilateral leg		
	PT1	PT2	SW75	PT1	PT2	SW75
Hip power sagittal plane (W)	718 ±144 627 ±123	662 ±119 725 ±170	659 ±132 648 ±155	885 ±347 502 ±123	760 ±346 580 ±209	677 ±240 628 ±190
Hip power frontal plane (W)	309 ±134 316 ±161	313 ±111 272 ±162	297 ±166 296 ±124	237 ±197 177 ±88	318 ±275 185 ±79	285 ±229 224 ±109
Knee power sagittal plane (W)	1037 ±266 1054 ±378	740 ±135 722 ±207	805 ±265 743 ±203	1060 ±308 925 ±277	904 ±270 784 ±337	911 ±281 960 ±352
Ankle power sagittal plane (W)	1196 ±290 958 ±295	1221 ±434 942 ±150	1178 ±254 956 ±177	**1977 ±533** **945 ±316**	**1944 ±272** **949 ±298**	**2096 ±311** **1336 ±408**

Two ways repeated measures ANOVA (with only the PT1, PT2 and SW75 techniques; Table 5.3) showed no significant effect of technique and dive height on peak contralateral hip power in the sagittal (p=0.69; p=0.77) and frontal planes (p=0.87; p=0.64), and ipsilateral hip power in the frontal plane (p=0.34; p=0.66) and knee power in the sagittal plane (p=0.33;

p=0.95). However, there was a main effect of height on peak contralateral ankle power in the sagittal plane ($p<0.05$), and ipsilateral hip ($p<0.05$) and ankle power in the sagittal plane ($p<0.05$). During high dives, peak contralateral ankle power and peak ipsilateral hip and ankle power in the sagittal plane were significantly ($p<0.05$) larger than during low dives (+275 W, +181 W, +956 W, respectively). In addition, there was a main effect of technique on peak ipsilateral ankle power in the sagittal plane ($p<0.01$). Pairwise comparisons showed that peak ipsilateral ankle power was significantly greater in SW75 than PT1 (+244 W; $p<0.05$) and PT2 (+325 W; $p<0.001$).

During high dives, the COM travelled over a larger horizontal distance (Figure 5.3, Table 5.4) in SW75 than PT1 (+9 cm; $p<0.01$) and PT2 (+5 cm; $p<0.01$). Furthermore, the COM travelled over a significantly larger vertical distance (Figure 5.4, Table 5.4) in SW75 than PT1 (+5 cm; $p<0.05$) and PT2 (+5 cm; $p<0.01$). In addition, the goalkeepers performed smaller countermovements (Figure 5.4, Table 5.4), COM at starting position – COM at the lowest position before contralateral push-off, during SW75 than PT1 (-6 cm; $p<0.01$) and PT2 (-4 cm; $p<0.05$).

These differences in COM trajectories were manifested in significant differences in average COM velocities. The horizontal velocity of COM at contralateral push-off (Figure 5.3, Table 5.4) was significantly greater in SW75 than in PT1 (+0.36 $m \cdot s^{-1}$; $p<0.01$) and PT2 (+0.26 $m \cdot s^{-1}$; $p<0.05$). Moreover, the peak negative vertical velocity of the COM (Figure 5.4, Table 5.4) was significantly smaller in SW75 than in PT1 (-0.4 $m \cdot s^{-1}$; $p<0.01$) and PT2 (-0.3 $m \cdot s^{-1}$; $p < 0.05$). Finally, the vertical velocity of COM at contralateral push-off (Figure 5.4, Table

5.4) was significantly greater in SW75 than in PT1 (+0.3 $m \cdot s^{-1}$; $p<0.05$) and PT2 (+0.3 $m \cdot s^{-1}$; $p<0.01$).

Table 5.4. Follow-up one-way repeated measures ANOVAs with technique (three levels: PT1, PT2, SW75) as a factor.

	Variables	PT1	PT2	SW75	P value
High Dives	Horizontal distance travelled by COM between CPF and IPF	59.5 cm	63.5 cm	68.5 cm	0.001
	Vertical distance travelled by COM between CPF and IPF	10.25 cm	9.88 cm	15.19 cm	0.009
	Countermovement	14.11 cm	11.61 cm	8.22 cm	0.001
	Horizontal COM velocity at contralateral push-off	1.07 $m \cdot s^{-1}$	1.17 $m \cdot s^{-1}$	1.43 $m \cdot s^{-1}$	0.003
	Peak negative COM vertical velocity	-0.82 $m \cdot s^{-1}$	-0.72 $m \cdot s^{-1}$	0.43 $m \cdot s^{-1}$	0.002
	Vertical COM velocity at contralateral push-off	-0.27 $m \cdot s^{-1}$	-0.25 $m \cdot s^{-1}$	0.01 $m \cdot s^{-1}$	0.006
Low Dives	Horizontal distance travelled by COM from dive onset to CPF	20.95 cm	23.94 cm	32.84 cm	0.004
	Vertical distance travelled by COM from dive onset to IPF	18.04 cm	15.94 cm	12.39 cm	0.008
	Horizontal COM velocity at contralateral push-off	0.59 $m \cdot s^{-1}$	0.68 $m \cdot s^{-1}$	0.96 $m \cdot s^{-1}$	0.005
	Vertical COM velocity variation	0.92 $m \cdot s^{-1}$	0.88 $m \cdot s^{-1}$	0.72 $m \cdot s^{-1}$	0.02

Discussion

In accordance with our hypothesis, the goalkeepers dived faster and contacted the ball earlier when starting with a SW wider than their preferred one. The optimal starting position, resulting in the fastest dive, was when SW was set to 75% of personal leg length and KA was at the preferred angle. All the modifications to the starting position were unaccustomed to the goalkeepers, thus the significant improvement is remarkable when taking into consideration the amount of hours spent training and performing using their preferred techniques. The changes in KA at the starting position lead to a reduction in goalkeeper's performance in the diving save.

The knee angle conditions (KA45, KA75, KA90) were significantly slower than all the other conditions. Modifying SW to SW75 did lead to a better performance that was significantly faster than all the other conditions, except PT2. A possible reason for the latter result is a learning effect that may have occurred towards the end of the experiment, as the SW at the starting position during PT2 was significantly greater than PT1.

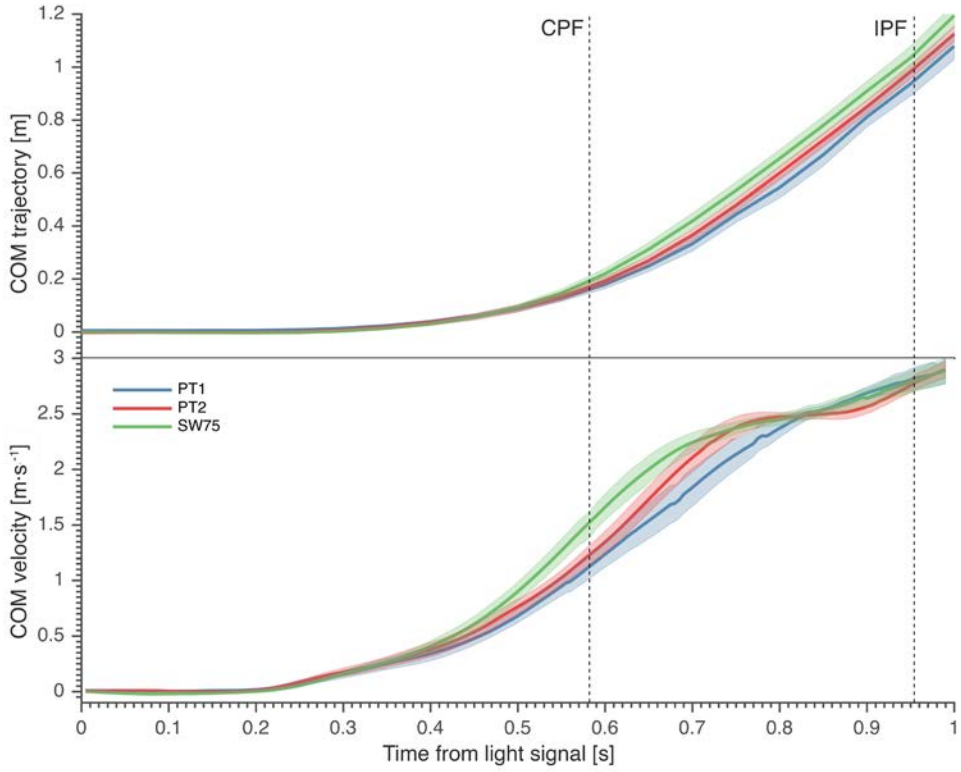

Figure 5.3. The average horizontal trajectory (Top) and horizontal velocity (Bottom) of goalkeepers' COM from light signal during high dives. The vertical dotted lines indicate the moment of contralateral peak force (CPF) and ipsilateral peak force (IPF), and the shading indicates the standard error.

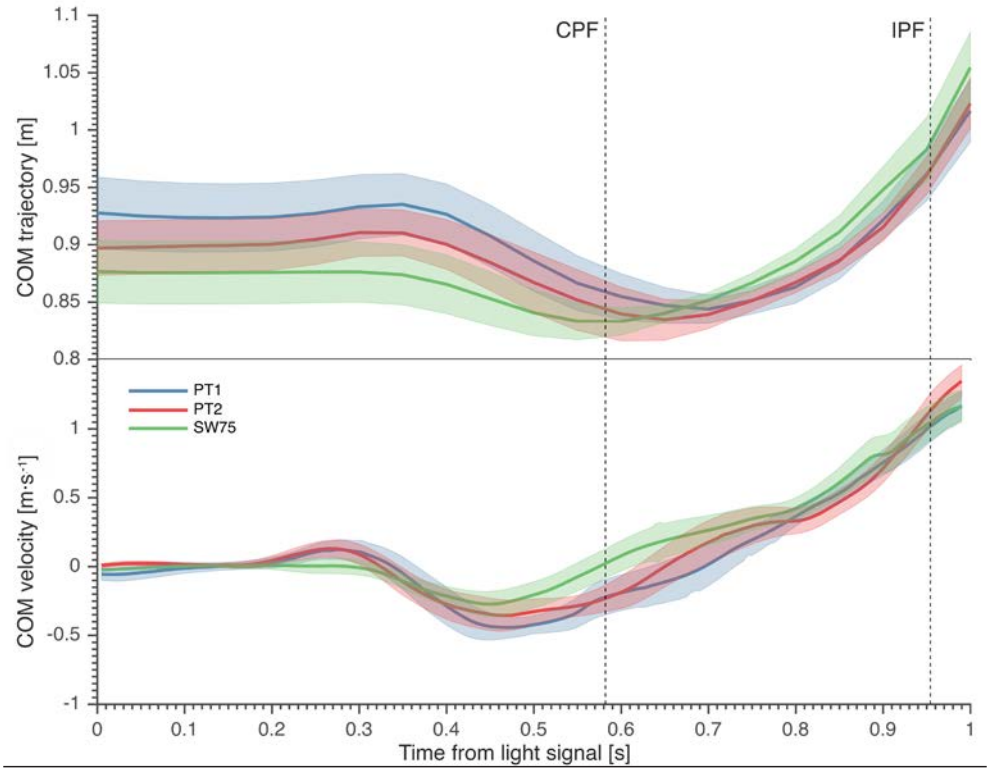

Figure 5.4. The average vertical trajectory (Top) and vertical velocity (Bottom) of goalkeepers' COM from light signal during high dives. The vertical dotted lines indicate the moment of contralateral peak force (CPF) and ipsilateral peak force (IPF), and the shading indicates the standard error.

In the PT dives for low balls, the goalkeepers started the dive by increasing their SW (Figure 5.2), with a small contralateral sidestep in the direction opposite to the dive and an ipsilateral sidestep in the direction of the dive. For high balls the increase in SW was usually achieved by performing only an ipsilateral sidestep in the direction of the dive. The resultant increase in SW reached a maximum, between the contralateral and ipsilateral peak forces, that was similar in magnitude (~90% leg length) and timing (~0.7 s after light signal) for PT1, PT2 and SW75. This was in accordance with findings of Ibrahim et al. (2018), where goalkeepers stepped sideways and increased their SW from 33% to 83% of leg length. Starting from a SW narrower

than SW75 takes more time for sidestepping and less time for application of force during the ipsilateral and contralateral push-off. The latter was partially evident, given that peak ipsilateral ankle power was significantly greater in SW75 than PT1 and PT2. It worth noting that when the goalkeeper started from SW100, they decreased SW to transfer from contralateral to ipsilateral push-off. During this condition, participants also did not benefit from any horizontal COM velocity towards the goal, given that there was no sidestep to increase SW. Therefore, a SW wider than 75% of leg length does not seem to further improve the diving save performance.

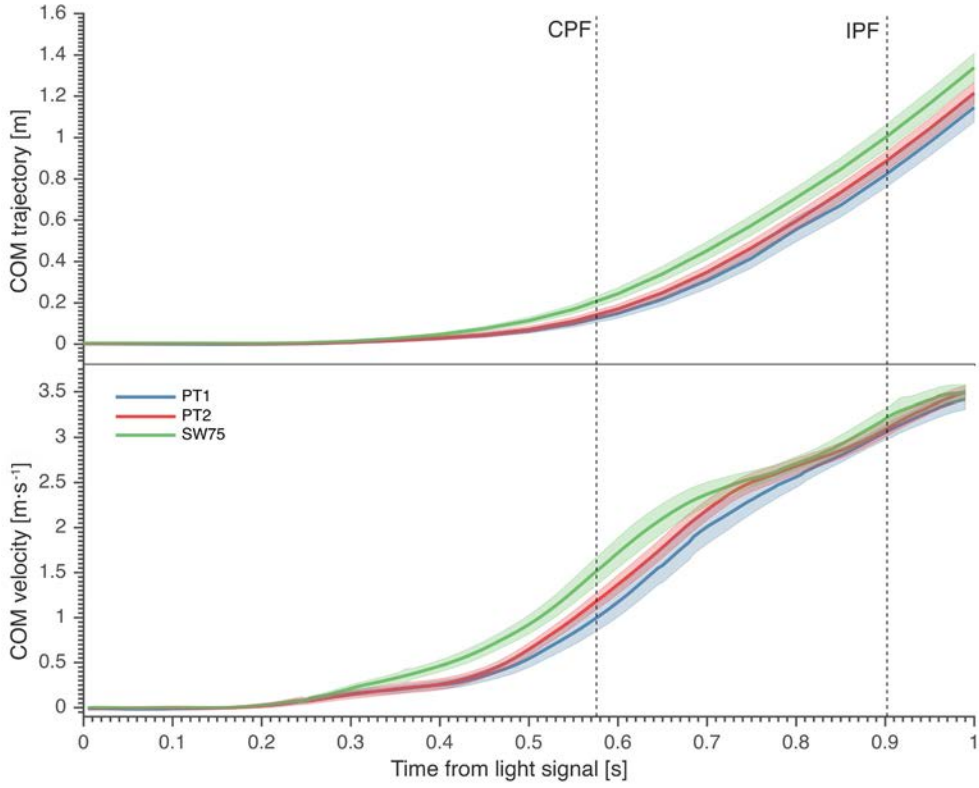

Figure 5.5. The average horizontal trajectory (Top) and horizontal velocity (Bottom) of goalkeepers' COM from light signal during low dives. The vertical dotted lines indicate the moment of contralateral peak force (CPF) and ipsilateral peak force (IPF), and the shading indicates the standard error.

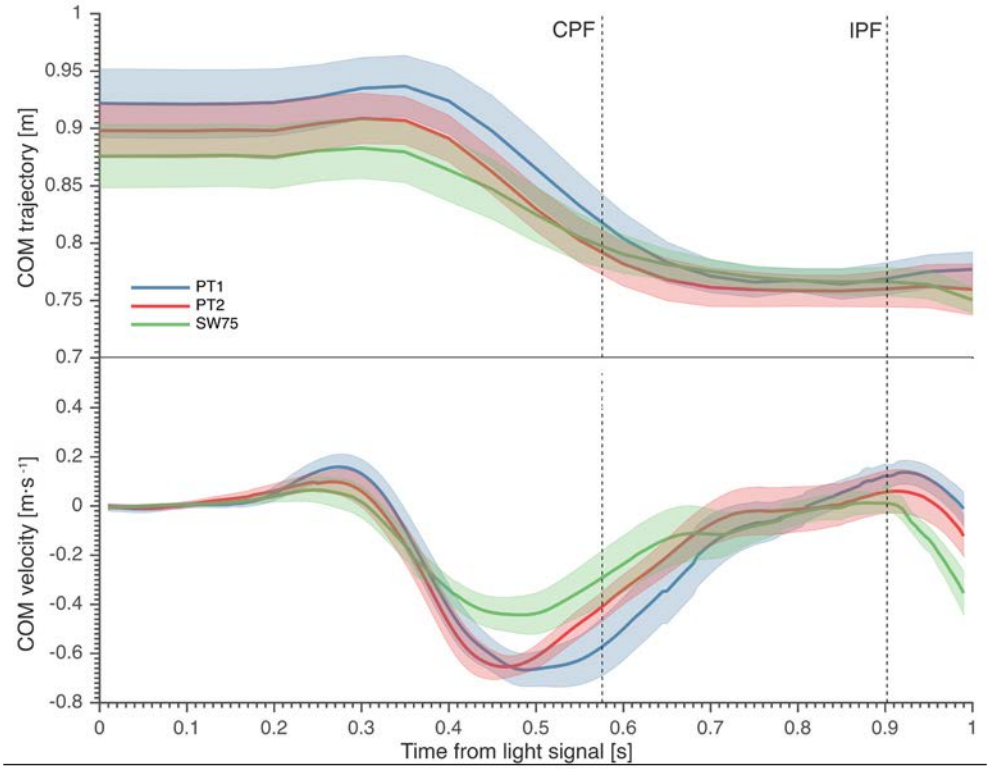

Figure 5.6. The average vertical trajectory (Top) and vertical velocity (Bottom) of goalkeepers' COM from light signal during low dives. The vertical dotted lines indicate the moment of contralateral peak force (CPF) and ipsilateral peak force (IPF), and the shading indicates the standard error.

Furthermore, being time-efficient in the transfer from contralateral to ipsilateral push-off was translated to the COM time series. During high dives, the body COM travelled over significantly larger horizontal and vertical distances between CPF and IPF in SW75 than in PT1 and PT2. There was also a significant increase, during low dives, in the horizontal distance travelled by the COM from dive onset to CPF, for SW75 compared to PT1 and PT2. The difference between techniques occurred earlier during low dives than high dives, which might be because the contralateral leg contributes more to the horizontal COM velocity during low dives than during

high dives[49]. The goalkeeper was also more efficient during SW75 as there was significantly less countermovement during high dives (COM at starting position – COM at the lowest position before contralateral push-off) and the COM travelled significantly less vertical distance during low dives.

This is not the first study that finds a characteristic of a sports movement in elite athletes to be less than optimal. Estevan et al. (2013) analysed the mechanics of the taekwondo roundhouse kick starting from three different stance positions (0°, 45°, 90°). They found that the kick is performed with shorter reaction and execution times when starting from a 0° and 45° stance positions, rather than starting from a 90° position which was more frequently adopted by coaches and athletes. Furthermore, Ball and Giblin (2009) studied the effect of SW in the starting position on movement time of field hockey goalkeeper corner saves. They found that a SW of 1.1 m, which was wider than the usually adopted SW by athletes, was the fastest.

A typical ball speed during a football penalty shot is about 75 $km \cdot h^{-1}$ [59,68.69]. The practical relevance of the relatively small time difference between SW75 and the average of PT1 and PT2 that we found (0.021 s) can be translated into the distance travelled by the ball and by how much further the goalkeeper can reach during that time. A ball traveling at 75 $km \cdot h^{-1}$ will be around 50 cm closer to the goal, during preferred technique conditions than SW75 when reaching the hand position of ball contact in the current setup. In addition, at the same point in time (instant of ball contact) the goalkeeper can reach about 15 cm further during SW75 than in preferred technique conditions.

Optimal training for the development of lower body power

should adhere to the principle of specificity[85]. Therefore, it might be beneficial to perform strength and conditioning exercises, and technical skill training from a SW equal to 75% of personal leg length. As the SW75 had not been trained in the present study, it is plausible that diving save performance differences with the preferred technique can be further improved after training. Therefore, we recommend to perform an intervention study to train the goalkeeper physically and technically on the diving save while starting from a SW equal to 75% of personal leg length. Such studies could aim to find out how far performance improves after that the goalkeepers actually train to dive from this unaccustomed preparatory posture.

Conclusion

In conclusion, elite football goalkeepers start the diving save using a preparatory posture that is sub-optimal for performance. Preparing for the dive with a stance width equal to 75% of individual leg length, which is wider than preferred, was optimal for all diving save directions and heights. When starting from this posture, goalkeepers were more performant at contralateral push-off, as more distance was travelled by the COM between contralateral and ipsilateral push-offs. The goalkeepers were also more efficient, as smaller countermovement and less variation in the vertical COM velocity occurred than in dives from their preferred posture.

Disclosure Statement

No potential conflict of interest was reported by the authors.

CHAPTER VI

Summary and General Discussion

Rony Ibrahim

In this thesis, mechanical analyses of athletes' movements were conducted in explosive sports offensive shooting and defensive jumping skills. The overall aim was to understand the nature and key determinants of performance of these movements, so that guidelines can be given to technical, and strength and conditioning coaches. To this end, two theories of coordination of explosive movements and the biomechanical principles behind them were explored in the first chapter. Thereafter, the drag flick shot in field hockey and the goalkeeper's diving save in football were chosen for further analysis.

Summary of Findings

In the **second chapter**, we investigated the coordination pattern used to maximize stick head speed when performing the drag flick in field hockey. Full-body three-dimensional kinematics of the drag flick was measured in elite hockey players, in order to analyze upper body joint angular velocity and contributions to stick endpoint speed. We found that the athletes timed the onset and peak magnitudes of trunk and upper limbs joint rotations largely in accordance with a proximal-to-distal sequence. The drag flick started by laterally rotating the trunk segment, followed by sequential onsets of right shoulder flexion, right elbow extension and right wrist flexion. As for the left upper limb, left wrist radial deviation and shoulder internal rotation started after the onset of trunk lateral rotation towards the target, and they were followed by onset of left wrist extension. Subsequently, peak angular rotation magnitude was reached first in trunk lateral rotation, followed by left shoulder internal rotation and wrist radial deviation,

while left wrist extension velocity peaked last. As for the right upper limb, right shoulder flexion reached peak velocity after trunk lateral rotation, followed by right wrist flexion and elbow extension. The deviations from a perfect proximal-to-distal sequence were attributed to constraints imposed by bi-articular muscles, the closed-chain formed by the upper limbs, and a required straight ball trajectory. In addition, not all rotations were equally relevant for maximizing endpoint velocity; trunk rotations (lateral and axial), right wrist flexion and left wrist extension were found to be the main contributors to endpoint velocity at ball release.

From the **third** to the **fifth chapter**, we focused on the mechanics of goalkeepers' diving save skill in football, by performing full body kinematics and lower limbs kinetics measurement of elite football goalkeepers. In the **third chapter**, we aimed to study the self-selected preparatory posture before the dive, the development of linear and angular momentum, and the legs' contribution to end-performance during high and low dives. Full-body three-dimensional kinematics were measured using a passive marker motion analysis system and ground reaction forces (GRF) were measured using two custom-made force plates. Balls were hanged with a magnet to a thin rope, 1 m in front of the goal line at two different heights (30 cm and 190 cm). During the preparatory posture, self-selected stance width was very consistent, with a relatively small standard deviation, compared to knee and hip flexion angles. We found little difference between dive heights in horizontal linear momentum, but the difference in vertical linear momentum was larger as high dives required more vertical displacement of the center of mass (COM) than low dives. Angular momentum in high and low dives were similar around contralateral push-

off, but differences started to appear around ipsilateral push-off as angular momentum during low dives continued to rise, while it dropped gradually during high dives. Furthermore, the contralateral leg contribution to COM horizontal and vertical velocity was larger than the ipsilateral leg contribution during all diving save conditions. The contralateral push-off lasted longer than the ipsilateral one allowing for a further forces build up and contribution to COM velocity. The contralateral leg was also better positioned in the direction of the ball, while the orientation of the ipsilateral leg was more upright and therefore more suitable for vertical linear momentum.

In the **fourth chapter**, we looked into lower extremity joint powers, moments and angular velocities in a more realistic experimental setup. The goalkeepers dived to save high and low balls, shot to both sides of the goal by a ball canon placed at the penalty spot. The shooting speed of the canon was calculated to make sure the goalkeepers had just enough time to react and dive as fast as possible to the correct side and height to save the ball. Similar to chapter three, a passive marker motion analysis system and two custom-made force plates were used to measure three-dimensional kinematics and kinetics of the goalkeeper's dive. We found a proximal-to-distal sequence, with some minor deviations, in timings of peak joint powers in both lower limbs. The joints of the contralateral leg reached their peak first by starting with the hip power in the sagittal plane, followed by knee power and ankle power in the sagittal plane, and hip power in the frontal plane. The contralateral peaks were followed by a perfect proximal-to-distal sequence of ipsilateral joint peak powers, as ipsilateral hip power in the sagittal and frontal planes reached peak magnitudes first, followed by knee power in the sagittal plane

and finally ankle power in the sagittal plane. Furthermore, hip extension and ankle plantar flexion moments in contralateral and ipsilateral legs were found to be the largest moments during push-off.

In the **fifth chapter**, we examined whether the performance of goalkeepers can be improved during the diving save. We independently altered knee angle and stance width at the starting position. In an experimental set-up similar to the one of the third chapter, three-dimensional kinematics and kinetics were measured in goalkeepers performing diving saves from: (1) their self-selected starting posture, (2) imposed knee flexion angles (45, 75 and 90 degrees), (3) imposed stance width (50, 75 and 100% of personal leg length). Stance width (SW) was left to the goalkeeper's choice when knee flexion angle (KA) was manipulated, and vice-versa. Remarkably, the self-selected starting posture was not the most optimal for end-performance. We found that starting the dive from a SW wider than the self-selected one, decreases the time required to save the ball and can therefore improve performance. The optimal SW between the ones tested, was equal to 75% of personal leg length (SW75). No positive effects of imposed KA on diving times were found.

In SW75, the COM had travelled more distance towards the target between contralateral and ipsilateral push-off, than in the self-selected preparatory posture, which we described as more explosive. Also, the goalkeeper performed a smaller countermovement when diving to high balls, and had a smaller vertical velocity when diving to low balls, than in the self-selected SW, which we described as more efficient.

Interpretation of results

The summation of speed principle and the principle of optimal coordination of partial-momenta, mentioned in the introduction (first chapter), are the two most studied coordination principles in sports skills with an aim to attain maximum distal-end velocity in a linked-segment model[78]. The summation of speed principle proposes that the movement is initiated by the heavy proximal segments with large moment of inertia, and as the movement progresses, the kinetic energy is transferred sequentially to the neighboring distal segment characterized by smaller moment of inertia[14]. This proximal-to-distal sequence is considered optimal when the distal segment starts its motion at the instant of peak velocity of the preceding proximal segment, allowing the distal segment to reach a higher velocity than the proximal one. However, the principle of optimal coordination of partial-momenta proposes that in order to reach the highest distal-end velocity, all the segments should reach their peak velocities simultaneously at the instant of release/hit/impact, while all joints are fully extended[43]. The summation of speed principle holds largely throughout this thesis, while the principle of optimal coordination of partial momenta does not apply. This is in line with other offensive shooting[26,33,52,73,98,99] and defensive jumping skills[11,12,18,72,96].

The first study in this thesis revealed a kinematic proximal-to-distal coordination pattern, adopted by elite hockey players when performing the drag flick. The pattern was not a perfect proximal-to-distal sequence in peak joint angular velocities, as some non-sagittal joint rotations took place earlier in the shot (i.e. shoulder internal/external rotation, wrist supination/pronation) than predicted based on this sequence. In the tennis

serve, similar non-sagittal rotations were found to be essential, as they significantly contributed to racket-head speed[64]. However, in the drag flick these rotations were of secondary importance, as their contributions to stick-head speed were relatively small, but they were key to two other main functions. First, they compensated for other joint movements, to keep the ball trajectory as straight as possible in the direction of the target. Second, they extended the moment arm of the trunk rotations to stick-head, allowing a greater gain of trunk angular velocities, which are low compared to the more distal joint angular velocities.

The main contributors to stick-head speed were trunk axial and lateral rotations, right wrist flexion and left wrist extension. The large contribution of trunk axial and lateral rotation to stick-head speed shows the importance of non-sagittal movements for performance and is similar to findings in tennis serve and baseball pitching[25,42,88,91]. This is to some extent in contrast with the general practice of strength and conditioning coaches, where most emphasis is placed on sagittal joint rotations (e.g. the variations of squat, deadlift, clean and jurk, snatch). They commonly use variations of weightlifting exercises when training athletes for sports where power, motor behavior, joint coordination contribute to athletes' performances[19]. However, the current results suggest that these practices may need to be revisited and updated based on the findings of biomechanical analysis on the athlete's movements in question. Drag flickers may benefit more from multi-planar exercises than from sagittal-plane weightlifting exercises. These multi-planar exercises should be initiated by the trunk segment allowing the upper limbs to lag behind (storing elastic potential energy), following which the trunk is stabilized (reversal of torques) allowing the

upper limbs to proceed with the motion (proximal stability for distal mobility). We are aware that these recommendations are somewhat incomplete without kinetic measurement, therefore follow-up studies need to incorporate upper limb kinetics measurements to develop more complete training guidelines.

Considering the relatively small wrist muscles and large peak stick-head speed attained, it seems quite impossible that right wrist flexion is a main generator for the stick-head speed. However, two things are to be considered; first, the stretch-shortening cycle may allow storing elastic potential energy in the wrist flexors through wrist extension (eccentric muscle activity). The stored elastic potential energy could then be used to amplify wrist flexion angular velocity[4,70,84]. The mechanical coupling between human body segments allowed for a lateral flexion of the trunk segment toward the target, while keeping the stick-head almost stationary on the ground, to be manifested as a right wrist extension and left wrist flexion which allowed the stick to lag behind the upper body by rotating at the wrists only. Second, Hirashima et al. (2008) found that in an overarm throwing movement, the proximal joint motions were mainly accelerated by joint torques at their own joints, while the distal joint motions were mainly accelerated by velocity-dependent torques of proximal joints. This has to do with Newton's third law, conservation and transfer of momentum and energy[78,84]. The resultant torques of muscle forces at a specific joint not only produce instantaneous and local acceleration at the same joint and connected body segments, but also influence the accelerations of the subsequent (distal) joints through proximal velocity-dependent torques[17,41,78].

In our study, it was not possible to calculate and analyze

velocity-dependent torques, because the drag flick is a closed chain movement in the upper limbs, and separate measurements of external forces on the upper limbs were not possible. Therefore, future studies can perhaps use a hockey stick instrumented with force transducers for the measurement of forces and moments applied to the stick by the right and left upper limb separately. The latter would allow estimation of the contributions of joint moments and even muscle forces to performance, which can further improve training guidelines.

In our second study (chapter 3), which was on a defensive jumping skill 'the goalkeeper's diving save', findings were not consistent with general coaching practices. In contrast to our first hypothesis, which was based on training recommendations of goalkeeper's technical, and strength and conditioning coaches, the contralateral leg contributed more than the ipsilateral leg to COM horizontal and vertical velocity toward the ball. This finding was due to better alignment of the contralateral leg with the direction of the dive and longer contact time.

This study was the first to develop and use an algorithm for automated detection of dive onset based on the work of Poor (1988), and Staude and Wolf (1999). It proved to be a successful objective method for detecting dive onset without being biased by differences in movement strategy.

In line with the first study, this study again showed the importance of non-sagittal plane movements with emphasis on the push-off with the contralateral leg. Joint rotations that produce these non-sagittal total body movements were elucidated in the third study. In that study (chapter 4), we analyzed the coordination and magnitudes of joint angular velocities, moments and powers in a near to real experimental

set-up. We first found a proximal-to-distal sequence in peak joint powers for contralateral and ipsilateral legs. To our knowledge, this was the first study to analyze joint kinetics of such a movement pattern. Unlike other vertical and horizontal jumping skills where both feet push-off and takeoff simultaneously, in the diving save the push-off and takeoff of both legs are separated in time. Therefore, we can say now that the proximal-to-distal sequence is still the selected coordination pattern for both legs, when involved in a multidirectional sequential push-offs, such as the goalkeeper's diving save. The analysis of joint power in the third study allowed us to give somewhat firm training recommendations to coaches about joint rotations that were the most important for the diving save performance. The latter was not possible in the first study, where only premature recommendations were given to coaches based on kinematic data only. Recommendations such as those given in the third study can be further enhanced if measurement of muscle activity would be performed along with the kinematic and kinetic measurements. Then, a complete training guideline can be given to coaches, by emphasizing the exact muscles that were responsible for generating the corresponding joint power.

The overall task in the first study was performed in the global sagittal plane, but it was mainly initiated by non-sagittal plane joint rotations (trunk lateral and axial rotations). In contrast, the second study showed that the goalkeeper's diving save, which is largely performed in the global frontal plane, is mainly driven by local sagittal plane motions and powers. The fact that the resultant body motion was mainly in the frontal plane, was due to the timing difference between the two legs. The hip extensors and ankle plantar-flexors produced the largest

joint power, supporting general coaching practices in training the triple extension of lower body joints[9,19,38,39,56,92]. Robertson and Fleming (1987) also found that the hip extensors and ankle plantar-flexors contributed the most to standing broad and vertical jumps, whereas the knees contributed the least. Still analysing information on which muscles specifically contribute to power generation is needed to complete the picture. Future studies are warranted to measure and analyze the latter, so that a definite update for technical and physical training guidelines can be made.

Based on the second study, the role of the ipsilateral leg at the beginning of the dive was to increase the stance width (SW) from around 33% of personal leg length to 88% and 77% for high and low dives respectively. Therefore, we hypothesized in the fourth study (Chapter 5) that starting at a stance width near to the maximum stance width reached before ipsilateral push-off, might allow the goalkeeper to be faster in the dive as less time is wasted to increase SW and more contact time is allowed for the ipsilateral leg. This hypothesis was confirmed in our fourth study, in which we found a significant improvement in dive time when goalkeepers adopted a SW equal to 75% of personal leg length (SW75). The goalkeepers' diving save was found to be more explosive and more efficient when starting from a SW equal to 75% of personal leg length. This explosivity was evidenced by the larger distance travelled at push-off by the COM toward the target, for SW75 compared to preferred technique. The COM travelled larger horizontal and vertical distances between contralateral push-off and ipsilateral push-off time instants for high dives, and between dive onset and contralateral push-off time instants for low dives. Increased efficiency was evidenced by the smaller countermovement

during high dives and reduced vertical distance travelled by the COM during low dives, for SW75 compared to preferred technique.

Conclusion

In general, a proximal-to-distal sequence seems to be the most adopted and probably most appropriate pattern for the explosive sports skills investigated. However, this sequence needs to be modified corresponding to the constraints imposed by the sports skill in question. This sequence seems to exist at multiple levels including the neuromuscular system, kinetics, and kinematics[84]. Even though it seems a very complex set-up, a detailed study combining measurements at different levels from the brain to kinematics is necessary for a complete understanding of the phenomenon and the link between levels. Such a study may provide detailed explanations as to why the proximal-to-distal sequence is the most preferred coordination pattern when it comes to practice, and how exactly it is coordinated.

We showed that a general movement plane is not always driven by joint rotations in the same plane. Also, we unexpectedly found that the leg opposite to the jumping side, which was not in contact with the ground at take-off, contributed more than the same side leg to the overall jump. Moreover, a completely unpracticed instruction (SW75) was found to result in better performance than the preferred and practiced technique. Consequently, our studies are an indication that there is still room for improvement of training and performance from a mechanical point of view. Detailed and targeted biomechanical analyses can help in doing so, and are accordingly warranted

for continued improvement.

CHAPTER VII

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CHAPTER VIII

Appendices

Appendix 2.1

Table indicating body segments and related bony landmarks used in the present study. Local axes systems were reconstructed based on the anatomical landmarks. In addition, cluster markers used to track motions of the respective segments are indicated. Note that leg segments are not used for the present analyses.

Body segments (related marker clusters)	Corresponding anatomical landmarks
Foot (shank)	2nd toe tip; Calcaneus; lateral and medial malleolus
Shank (shank)	Lateral and medial malleolus; lateral and medial femur epicondyles
Thigh (shank and pelvis)	Lateral and medial femur epicondyles; greater trochanter
Pelvis (pelvis)	Right and left antero-superior iliac spines; midpoint between the postero-superior iliac spines; navel
Abdomen (thorax)	Navel; 12th thoracic (T12); xiphoid process
Thorax (thorax)	Xiphoid process; 6th thoracic (T6); supra-sternal; 7th cervical (C7)
Head (thorax)	7th cervical (C7); right and left tragion; head vertex
Upper arm (upper arm)	Acromion process; lateral and medial humeral epicondyles
Forearm (forearm)	Lateral and medial humeral epicondyles; radial and ulnar styloids

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About the author

Rony Ibrahim was born on the 6th of September 1989, in Zalka, Lebanon. After graduating with a bachelor degree in Physical Education and Sports at Antonine University, Lebanon, he sought to deepen his knowledge in sports sciences. He moved to the Netherlands to pursue his master's degree in Human Movement Sciences: Sports, Exercise and Health at Vrije Universiteit Amsterdam. During his master's research internship, he performed research in the area of sports biomechanics, where he became very enthusiastic about analyzing, understanding and optimizing athletes' movement. To share this passion, he became an assistant teacher for the master's course of Sports Biomechanics in 2013 at Vrije Universiteit Amsterdam.

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List of publications

Ibrahim, R., Kingma, I., de Boode V.A., Faber, G.S., & van Dieën, J.H. The effect of preparatory posture on goalkeeper's diving save performance in football. (Under review).

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